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Mr G. M. McNaughton, Member, Chairman of the Division, in the Chair

The following Lecture (illustrated by a film) was delivered and, on the motion of the Chairman, the thanks of the Division were accorded to the Lecturer.

"The Sardinian Project—An Experiment in Malaria Control by Species Eradication"

by
John Alexander Logan, D.Sc., M.A.S.C.E.

SINCE the dawn of history man has been engaged in a relentless war against disease, and insects, many of which are important vectors of a number of diseases, have been important participants in this war. Although it has only been within relatively recent time that their role has been recognized, they have, recognized or not, had a predominant part in the shaping of the events of history. As Hans Zinsser, the eminent American scientist, said in his classic "Rats, Lice, and History": "Swords and lances, arrows, machine guns, and even high explosives have had far less power over the fates of the nations than the typhus louse, the plague flea, and the yellow-fever mosquito. Civilizations have retreated from the plasmodium of malaria, and armies have crumbled into rabbles under the onslaught of cholera spirilla, or of dysentery and typhoid bacilli. Huge areas have been devastated by the trypanosome that travels on the wings of the tsetse

fly. . . . War and conquest and that herd existence which is an accompaniment of what we call civilization have merely set the stage for these more powerful agents of human tragedy."

The Pioneers

It was not until 1880, however, that the first of a small group of medical pioneers, working in isolation in remote corners of the world, obtained the first scientific evidence which incriminated insects as vectors of disease. In that year Dr Patrick Manson, a Scottish medical officer with the Chinese Imperial Customs Union in Formosa, demonstrated conclusively that elephantiasis was carried by mosquitoes. In 1890, two Americans, Theobald Smith and F. L. Kilbourne, showed that insects could transmit disease from one animal to another, when they proved that cattle ticks were the intermediary hosts in the transmission of Texas cattle fever. In 1896, Dr David Bruce of the British Colonial Medical Service in Zululand proved that tsetse flies could carry the trypanosome parasite of sleeping sickness from animal to animal, and in 1897 Dr (later Sir) Ronald Ross in India made one of the most important of medical discoveries when he found the parasites of malaria in anopheline mosquitoes. Since that time research and investigation have been greatly extended and mites, fleas, sandflies, and a number of other insects have also been shown to be the primary vectors in the transmission of such important diseases as typhus, plague, trench fever, and kala-azar.

Insect Control

It was not until man knew the cause of insect-borne disease that he could do very much about controlling it, although the rise of sanitation and the increased standard of living during the nineteenth century did reduce the incidence in the more developed parts of the world. At the turn of the century, however, malaria, probably the most important single cause of death and disability in the world, still dominated life over a vast part of the globe. In a more limited and more tropical range yellow fever was rampant. Sleeping sickness controlled the central part of the African continent and typhus and plague were endemic throughout most of the world, ready to blaze into epidemic proportions whenever a breakdown in normal living conditions occurred.

It is to Sir Ronald Ross that we are indebted for the first rational method of controlling insect-borne disease, that of controlling the insect vector. Although this theory was originally considered as impracticable, General William Crawford Gorgas gave a brilliant demonstration of its validity when he eliminated yellow fever from Havana in 1901 by a vigorous anti-mosquito campaign. This success led to the selection of Gorgas by the United States Government as Director of Sanitation for the new Panama

Canal project and he, in turn, appointed a civil engineer, Mr J. A. LePrince, as his Chief Sanitary Inspector. The success of these two men is legendary and their work virtually made the completion of the canal possible, constituting, as Dr A. J. Warren of The Rockefeller Foundation has said, "an epic in the history of sanitation and preventive medicine."

In Malaya, on the other side of the world, Sir Malcolm Watson was demonstrating, in a less spectacular way, the no less dramatic effect of anopheline control in the suppression of malaria. Sir Malcolm's work was instrumental in narrowing the "mosquito reduction" theory of Ross to "species sanitation," following the realization that only certain species of anophelines were responsible for malaria transmission.

Mosquito-control measures were originally based on general sanitation, screening, drainage, oil larviciding, and fumigation. Spray insecticides were used for the first time about 1928 in controlling a yellow fever epidemic in Rio de Janeiro. Later, pyrethrum was successfully used for malaria-control purposes in such widely separated countries as Zululand and India. In Brazil, Dr F. L. Soper, Dr D. B. Wilson, and their co-workers, by a vigorous application of species sanitation measures against *Aedes aegypti* realized the possibility, not only of reducing the vector to a level which would break the yellow-fever transmission chain, but also of eliminating the species entirely. The organization and techniques developed for this purpose were suddenly put to an even more rigorous test when they were used to eradicate the malaria vector *Anopheles gambiae* from north-east Brazil. A small number of these dangerous mosquitoes had been brought over from Africa in 1933 by a fast French gunboat, and their rapid spread threatened the entire continent with epidemic malaria. The record of this invasion and its dramatic elimination now forms a brilliant chapter in the history of insect control. The value of the eradication technique which was developed was again demonstrated when an invasion of *gambiae* was stopped and eradicated from Upper Egypt in 1945.

The New Synthetic Insecticides

As the work of Manson, Ross, Gorgas, and Watson is remembered because of its importance in the development of a rational method of insect control, that of Paul Müller stands out as the pioneer in a new, more modern, era. Working in Basle, Switzerland, in the years 1936–37, he discovered the insecticidal properties of the synthetic chemical compound dichloro-diphenyl-trichloroethane (DDT), which was first prepared by Zeidler in Germany in 1874. In 1942, when Wiesman in Switzerland noted that this material had a prolonged residual effect against houseflies, it was apparent that DDT had many of the properties of the ideal insecticide ; it was stable so that it could be shipped and stored ; it was highly lethal in small quantities against a number of insects, it was relatively safe to man, and its residual effect was a new and extremely desirable property in the

field of insecticides. The possibilities inherent in this new material were immediately perceived by both the British and the United States Armed Forces and small quantities were obtained for test purposes. The initial tests indicated the potency of DDT against such insects as lice, houseflies, and bedbugs, and arrangements were made to put it into commercial production.

In 1942, benzene hexachloride (BHC) was discovered in the United Kingdom, and also proved to be a remarkable insecticide with a number of unique qualities. Later, other new synthetic toxicants such as chlordane, dieldrin, and aldrin were developed and became available commercially.

Tests carried out during the latter part of the war indicated the efficiency of DDT as a residual spray against malaria, and as the war ended a number of countries planned to initiate national programmes based on this method. However, whilst residual spraying had shown great promise it was not certain whether it would prove to be an economic or a practical means of control on such a wide basis. The advent of DDT, BHC, and the other residual insecticides had found malaria, plague, yellow fever, and other insect-borne diseases retreating from limited areas of the world because of improved sanitation, land reclamation, screening, and the use of household insecticides. However, as the situation in Italy during the war demonstrated, both malaria and typhus were ready to return in epidemic proportions when given an opportunity such as was provided by the breakdown in normal living conditions.

The Proposed Sardinian Experiment

Since DDT also proved to be an effective method of controlling larvae when used as a larvicide, it was believed that a combination of DDT residual spraying together with larviciding would greatly improve the efficiency and extend the use of the species-eradication technique. While these new possibilities were under consideration in different parts of the world, it actually became possible to initiate a project in Italy because of a combination of fortuitous circumstances. At the end of the war, UNRRA, the United Nations Relief and Rehabilitation Administration, was investigating possibilities for permanent investments in the future of Italy. A Lire Fund had been established from counterpart funds set up against imported UNRRA supplies, and whilst most of these funds were used for work-relief purposes, Mr S. M. Keeny, the director, was anxious to set aside a proportion of the Fund for permanent works. The eradication of the malaria vector *Anopheles labranchiae* from the island of Sardinia was suggested as such a project and The Rockefeller Foundation was approached regarding their interest and participation.

Malaria had existed in Italy for centuries and the mosquito vectors had been demonstrated to be indigenous. Since many scientists believed

that the success achieved in Brazil and Egypt was attributable to the fact that the mosquito eradicated was in each case an invading and not a domestic species, the next logical development in the use of eradication technique was an attempt to use it in an area such as Sardinia against an indigenous vector. The Foundation, therefore, agreed to provide technical direction for the project as an experiment to investigate the practicability of the eradication technique as a method of malaria control. Besides funds, transport and equipment were also promised by UNRRA, and the full co-operation of the Italian Government was assured.

The project was conceived as an application of modern scientific developments on a large-scale experimental basis. It was planned to use the entire island for the experiment because it was believed that many of the problems and difficulties inherent to eradication could be discovered only by full-scale operations. Whilst it was originally thought that time and financial limits for the project could be readily estimated, this proved to be wrong, and a number of extensions of both time and budget had to be made. Within these flexible limitations, however, funds and equipment were available on a generous scale, and this made it possible to employ any method or equipment which might reasonably be expected to assist in eradication. The planning, the training, and the intensity of operations were in keeping with the magnitude of the expenditure and the value of a successful demonstration of eradication both to Sardinia and Italy, and the rest of the world.

Sardinia

Sardinia proved to be a particularly difficult area in which to test the species eradication technique because of its topography, its size, and its primitive state of development. Whilst several anopheline species were known to exist, only one of these, *labranchiae*, was known to be a malaria vector and Professor Alberto Missiroli, the prominent Italian biologist, believed Sardinia to be the epicentre of its range. Whilst Italy has been notorious for malaria in the Western world since the time of the Greek and Roman empires, Sardinia, at least in modern times, had been considered as the most malarious part of the country. It was also the least cultivated area, and had the lowest population density.

It is the second largest island in the Mediterranean (following Sicily), having an area of 23,896 square kilometres (9,226 square miles) and a population of 1,250,000. It has a semi-tropical climate with relatively hot summers and with moderate rainfall and occasional snow storms during the winter. It is a rough and primitive land of hills and mountains with scattered villages and large sections not served by either road or railway. A considerable portion of the coastal area is flat and fringed with swamps and brackish or salt-water lagoons and the river systems have shallow tortuous beds, choked with vegetation. Mountain streams also contain

heavy growths of vegetation, and upland and mountain swamps are common. Small-scale irrigation, consisting of stream blockage and flooding, is widely practised. Although a number of planned reclamation projects have been developed, many of them have been neglected and abandoned.

Operations

On October 1st, 1945, the International Health Division of The Rockefeller Foundation agreed to assume technical direction of the proposed eradication project and on April 12th, 1946, a special agency of the Italian High Commission for Hygiene and Public Health, known as ERLAAS,* was established to carry it out. Finance was arranged through counterpart funds made available by UNRRA and later by the Economic Co-operation Administration (ECA). The project was initiated early in 1946 and was concluded in 1950.

Based on the experience of Brazil and Egypt the island was divided into sectors, each comprising an area of approximately 4·5 square kilometres (1·73 square miles), distinctly indicated both on maps and in the field. These served as the basis for both larviciding and scouting operations. Owing to a lack of trained personnel, training schools were established for instructing residual spray operators, larviciders, scouts, and auxiliary personnel. The operations were carried out as follows :—

1946	Entomological survey.
1946–47	Residual spraying campaign against over-wintering *labranchiae* for training purposes and to suppress malaria transmission.
1947	Larviciding in a test area.
1947–48	Winter residual spraying of all man-built structures in Sardinia with 2·0 grammes of DDT per square metre of wall and ceiling surface (0·2 gramme per square foot).
1948	Larviciding of all fresh-water surfaces on the island on a weekly-cycle basis using a DDT-oil-Triton larvicide.
1948–49	Mop-up residual spraying.
1949	Mop-up larviciding.
1950	Check on eradication plus additional larviciding.

Owing to the extent of the undeveloped and uninhabited areas the problem of logistics proved particularly difficult and it was found necessary to build large numbers of field camps to serve these areas. Supplies and men were transported by a fleet of more than 250 ex-army jeeps and weapon-carriers, aided by animal transport. Fog generators and DDT smoke canisters were used to supplement the residual spraying operations,

* Ente Regionale per la Lotta Anti Anofelica in Sardegna.

and aeroplanes, helicopters, boats, rafts, and specially designed larvicide "bubblers" were used in the larviciding programme.

Because of the necessity of preparing water surfaces for efficient larviciding, considerable clearing and drainage work was necessary. Most of this was done by hand, but ditching dynamite, and tractor- and animal-drawn ditchers were also used. This part of the programme required a large labour force and the number of ERLAAS workers at one time (August 1948) amounted to more than 33,500.

The cost of the project amounted to more than six billion lire as compared with the two billion lire originally estimated, and took more than $4\frac{1}{2}$ years instead of the year originally planned.

Results

As a result of ERLAAS operations, malaria as a public health problem has been eliminated from Sardinia. The number of cases, including primary infections, re-infections, and relapses, fell from the maximum of 78,173 in 1944 to 44 in 1950 and 9 in 1951. No new cases were verified in 1950, and of the 9 cases reported in 1951, only one was considered as a possible primary infection. The number of cases (unverified) reported by provinces for the years 1944–51 is indicated in Table 1.

Table 1.—Cases of malaria reported in Sardinia, by province and by year, from 1944 to 1951

(From monthly reports of Provincial Medical Officers)

Year	Cagliari		Sassari		Nuoro		Island total	
	New cases *	Total cases	New cases *	Total cases	New cases *	Total cases	New cases *	Total cases
1944	4,275	18,423	2,424	29,814	4,478	29,936	11,177	78,173
1945	3,109	15,669	2,559	34,564	2,851	24,408	8,519	74,641
1946	3,206	17,186	4,180	38,655	2,763	19,606	10,149	75,447
1947	861	6,470	1,862	25,181	245	7,652	2,968	39,303
1948	125	1,631	207	10,967	9	2,523	341	15,121
1949	3	173	2	922	1	219	6	1,314
1950	2	34	1	9	1	1	4	44
1951		(Data	not avail	able by P	rovinces)		3	9

* The term "new cases" includes all primary cases and re-infections reported. In 1950 and 1951 these cases were later investigated by the ERLAAS medical staff for confirmation.

The reduction in spleen and parasite indices, although following the same downward trend as that of malaria itself, was relatively slower, which is probably an indication of the previous degree of endemicity of the

disease in the island. Beginning in the fall of 1948, blood examinations were made of all infants between 2 months and 2 years of age in the test villages. Five infants out of 871 examined during the first survey were found to be parasite-positive; thereafter no positives were found in infants.

Unfortunately, the success achieved in the reduction of malaria was not accompanied by the eradication of *labranchiae*. After apparently clearing most of the island in 1948 following the island-wide programme, the species continued to appear in 1949, 1950, and 1951, although always in extremely small numbers. During the entomological survey in 1946 *labranchiae* was by far the dominant species; 63 per cent of all inspections were positive for anophelines and more than 90 per cent of these were for *labranchiae*. By 1950, however, it took more than 330 scout-days to find a collection, or, in other words, it would have taken a trained scout more than a year to locate a single *labranchiae* infestation. There was also a great decrease in the size of the collections. In 1946, collections of immature stages ranged from three to twelve per dip. In 1950, of the 420 *labranchiae* collections made as a result of over 2,200,000 larval inspections, a total of 1,379 specimens were collected and many of the collections consisted of a single specimen only. Eleven *labranchiae* adults were found in twelve collections following 178,279 inspections.

But *labranchiae*, even though in extremely small numbers, continued to exist and it was evident that eradication had not been achieved. Often sectors were found positive after they had apparently been free of *labranchiae* for as long as 2 years. Although the extent of the initial destruction was comparable to that achieved in Brazil and Egypt, the population curve did not approach zero, as in these former campaigns, but flattened out as eradication appeared imminent.

It was evident that indigenous species such as *labranchiae* have a whole series of survival characteristics which have been developed over literally tens of thousands of years, and that these normally make them much more difficult to eradicate than an imported species. The project focused attention on the shortage of data regarding the ecology and the physiology of anophelines, and the need for more information about the action of insecticides. It also emphasized the importance of research and investigation as a fundamental part of insect-control work and the difficulty of extending operations beyond the limits of existing scientific knowledge.

In carrying out the project, more than 30,000 hectares (74,000 acres) of land were reclaimed by drainage operations. The planning of drainage, larviciding and residual spraying work made it necessary to consider the island as a geographic whole and this led to a consideration of its overall problems and potentialities. From this point of view, the extent of the uncultivated and unused land, the sparseness of the population, and the lack of knowledge of the island's social and economic resources were evident. Since ERLAAS made it possible for the first time to live and

work anywhere on the island, opportunities for development existed which had never before been possible. With the pressure of excess population on the Italian mainland it seemed logical that a study be made to examine the possibility of Sardinian development over a long-range period, with particular reference to its ability to absorb people from the Continent. This social economic survey is now under way and its recommendations may well prove to be the most important result of the project.

Summary

In Sardinia, under conditions which were difficult but not abnormal, after an intensive and costly effort over a period of 4½ years, the eradication of *Anopheles labranchiae* was not achieved. Although it appeared to be imminent in 1950 it was not possible to make any definite commitments for the attainment of eradication, with regard to either additional time or expense. It was believed, however, that the most economic method of control would be a continuation of eradication pressure on a maintenance basis over a period of years and that this would give the possibility of eventual eradication. This programme is now being carried out by the Regional Government.

From the evidence furnished by ERLAAS, the eradication of an indigenous anopheline such as *labranchiae* is a difficult and expensive proposition. In Sardinia, from the standpoint of malaria control, the residual spraying method would have been both cheaper and easier to operate. The use of eradication may, nevertheless, offer some advantages under certain special conditions, particularly if incorporated in a general conservation and development programme where part of the cost could be charged to rehabilitation. Apart from its application in malaria control the technique as used in Sardinia, or some modification of it, may have a limited field of use against other insects in both the medical and agricultural fields. It remains, therefore, as a potent though expensive possibility in any situation where man is engaged in raising living standards by the suppression or elimination of harmful insects. Eradication should be based on an accurate knowledge of the biology of the vector involved and provision should be made to utilize any equipment or method which seem advisable under the circumstances. The project should not be rigidly confined by time or finance.

Conclusion

We are, at the present time, living in what has been called the "Golden Age" of insect control and the eradication technique is only one of the many which can be used. Through the use of insect control, together with preventive medicine and environmental sanitation, man can now live and work in safety anywhere in the world. Areas which were at one time

considered as "white man's graveyards" can be made as free from disease as a typical community in the United Kingdom or the United States. Malaria is ceasing to be a public-health problem in an increasingly large part of the world; yellow fever has now been conquered; African sleeping sickness is no longer the dread disease that it once was and is now essentially a veterinary problem; typhus fever made only a sporadic appearance during the last war and was rapidly wiped out wherever it was found.

The situation is of particular importance to engineers, particularly those engaged in public health work. At present the development of the backward areas of the world is progressing at an intensity which has never before been seen and it has acquired a new social and political significance. In many parts of the world pioneer teams consisting of doctors, engineers, and biologists are extending the frontiers of health prior to development and are eliminating the hazard from many areas where disease was at one time considered as an insurmountable obstacle. Insect control is proving to be a vital factor in the rational development of these areas, and it is hoped that the ERLAAS experiment has been able to make a modest contribution to this important new era.

During 1952 the work of ERLAAS has been followed up by a Foundation research team and it is interesting to note that there have been no cases of malaria reported in Sardinia during the year.

There has been another observation, this one of a biological nature, which may lead to important developments. Because *labranchiae* once dominated the mosquito population of the island, it was assumed to have a high reproductive capacity, or "biotic potential," and the success of the ERLAAS project had indirectly been based on this assumption. The importance of a high biotic potential had been evident in Brazil and Egypt, when, after working intensively in a given area until *gambiae* had apparently been eliminated, the success or failure of the work could be readily evaluated within a short period of time by the continued presence or absence of these mosquitoes. If any remained after treatment, their reproductive capacity was such that their numbers rapidly increased to a point where they were readily detected, and a new effort at eradication could be initiated. An observation period of 6 weeks after the completion of eradication measures was normally found to be sufficient to establish the success or failure of eradication.

It will be recalled that, in Sardinia, *labranchiae* were found in small numbers for as long as 2 or 3 years after treatment had terminated in areas believed to have been cleared. Some factor, not evident in either the Brazilian or Egyptian campaigns, was evidently preventing the rapid increase of the species to their former position of domination.

During 1952 more information was obtained concerning this phenomenon. Three biologists and a considerable number of scouts had under

observation an entire river basin in which a single *labranchiae* larva was found early in the year. This valley had not been found positive for *labranchiae* since 1948 and had had no form of anti-mosquito treatment since that time. The surprising thing was that, even in 1952, no rapid development of the species occurred, and, in spite of their apparent freedom to develop at will, not more than a total of 100 specimens were observed. On the other hand, *Anopheles hispaniola*, a new anopheline to this area (and not a vector of malaria), was found to be the dominant species, having taken over the role formerly occupied by *labranchiae*.

Questions

Mr J. B. K. Ley asked the Lecturer whether, apart from the effect on the mosquitoes, there had been any upsetting of biological balance in Sardinia as a result of the work carried out.

The Lecturer, in reply, said that that was a question which was frequently asked, and that the answer was "No, with reservations." The ERLAAS programme was directed essentially at mosquitoes and did not involve a widespread treatment of the entire island; treatment was directed specifically at mosquito breeding- and resting-places. That concentrated treatment had prevented the wholesale destruction of insect and bird life which had been reported in some other instances. The reservations were that, in the attempt to eradicate *labranchiae*, other insects, such as houseflies, had been affected. During the early years of the campaign it had been difficult to find houseflies anywhere on the island, but they had returned in large numbers and did not now appear to be very "upset." Fleas and sandflies, however, which would normally be found in houses, had disappeared. With the exception of those insects there had been no changes observed in the population of such things as snakes, frogs, dragonflies, or birds. Since the insects affected were considered as harmful, their control was welcomed by the community.

Professor A. J. S. Pippard observed that in a world in which science received most recognition when it was used for the destruction of human beings on a mass scale, the story which had been unfolded by the Lecturer, supported by a magnificent film, was most refreshing.

It appeared from the Lecturer's remarks that a new mosquito had established itself as the old one was eradicated, and it would be interesting to know if that was a usual occurrence. Was it a general rule that different species—if species was the right word—were incompatible in that way? Why could not those two species exist together? There appeared to be grounds for hope in that phenomenon that the malaria vectors might be overcome by introducing stronger antagonistic species which were harmless to human beings but would eliminate the dangerous type.

The Lecturer, in reply, said that there was not enough biological information available to answer the question. Dr Trapido, one of the

Foundation biologists who had worked in Sardinia during the past summer, had expressed the position very well when he had said that if mosquitoes were as large as horses, much more would be known about them! The fact that mosquitoes were small made them difficult to study, and even though they were considered to be one of the most widely studied insects in the world, one of the major lessons which had come out of the project was the lack of basic biological knowledge about them.

An important problem was that of the difference between "strain" and "species." All dogs, for example, belonged to the same species since they were inter-fertile (the accepted test for a species), but there were many strains of dogs, such as pointers, setters, and hounds, and in those separate groups wide variations were displayed by individuals. Mosquitoes, however, were so small that, although it was possible to classify them according to accepted species, very little was known about strains. Both the mosquito near elimination in Sardinia (*labranchiae*) and the new invader (*hispaniola*) were considered to be "species." Only small numbers of *hispaniola* had been found prior to the ERLAAS campaign, but it was now plentiful and was taking over the living space of *labranchiae*. It was not clear why it was able to do so. So far as was known, there was no "war" between the two species, and the only apparent answer was that they occupied the space and used food for which the other species might normally be in competition. The other possibility was that the surviving *labranchiae* were of a particular strain with different living habits from the other strains of the species which had been eliminated. The surviving strain might or might not be a malaria vector.

Dr J. A. E. Galley said that that was a very interesting observation and a study of it might reveal alternative methods of control if the right species could be introduced. The introduction of predators and parasites had been shown to provide an excellent biological method of control of a limited number of pests, but that was a rather different phenomenon, which required further study by biologists.

Mr J. L. Hitchon said that parasites and predators had been introduced in experimental work carried out in Canada. With hundreds of thousands of square miles of territory it had not been possible to tackle the problem from the chemical angle, and other insects had been used to control the pest. Not sufficient was known as yet about the mosquito to say what the possibilities of that method were in that direction.

Mr F. E. Bruce asked the Lecturer whether, if he were faced with the problem of tackling malaria in Sardinia all over again, his line of attack would be any different. Mr Bruce said he had in mind particularly the balance between the use of insecticides and other methods such as drainage and water control, because there was a school of thought which tended to decry the use of drainage methods and claimed that insecticides were rendering such methods relatively unimportant.

The Lecturer, in reply, explained that ERLAAS had been made

possible because there had happened to be a considerable amount of surplus equipment and relief funds available in Italy after the war. That situation had provided an opportunity for a large-scale experiment designed to test the practicability of a new technique in malaria control. Since the situation had been of a temporary nature, it had not provided time for the advance planning and investigation which would normally have been considered necessary. It had been decided that the methods already proven in Brazil and Egypt against an invading anopheline offered a reasonable hope of success in Sardinia. However, if a " one sentence " explanation could be given for the failure to eradicate, it was because field operations had been conducted using a method which had not been adequately explored from a scientific point of view; the ERLAAS laboratories had not been extensive enough to solve the scientific problems which arose, fast enough to guide the operations.

If the project could be repeated, priority would be given to the establishment of an adequate laboratory equipped for both research and investigation, since, on the basis of existing knowledge, eradication could not be guaranteed, particularly within a limited period of time. It was believed, however, that success could be obtained if sufficient time was allowed, and that brought up the possibility of combining eradication with an island-wide programme of reclamation. In view of the fact that Sardinia was both under-populated and under-developed, a combined project of that kind offered a number of advantages. In that way the ditching and drainage work could be rationally designed to serve for both agricultural and malaria-control purposes.

The question of the resistance of insects to chemical insecticides also entered the picture. Fortunately, the only anopheline species so far found resistant to DDT was one in Panama. However, as an indirect consequence of resistance, it was now being found in parts of Italy that some malaria was returning, not because of mosquito resistance to DDT, but because DDT could not control houseflies. As a result, the necessary co-operation in permitting sprayers to enter houses had not been forthcoming from householders. If that practice became widespread it could reduce the treatment area sufficiently to make a serious break-through of malaria possible.

It could be said, therefore, that the events of recent years had served to emphasize the importance of permanent engineering work as a factor in the control of malaria. The widespread use of insecticides, however, tended to limit their use in particular situations.

Mr A. A. Gross said he was a little puzzled by the fact that, with the use of larvicide, where the oil was the main factor in making a film on top of the water, so much DDT was used as well. Was that in order to help the oil to spread, to catch the returning adult, or did it help to poison the larvae?

The Lecturer, in reply, said that before the use of DDT, oil had been

used as a larvicide in its own right. It had been found that the addition of DDT made the larvicide more effective. The oil in that case acted essentially as an agent to obtain effective coverage of the DDT on the water surface, and it was the DDT rather than the oil which appeared to produce death. Death was produced by the DDT acting as a stomach poison, ingested by way of the larval tracheae.

Although good control of larvae was normally obtained in Sardinia through the use of the DDT larvicides, it was occasionally found, in pan tests, that all of the larvae were not killed even after 13 or 14 hours' exposure. That lengthy period of survival had led to field tests, and it had been found that, although the larvicide normally used had a high spreading power (more than 40 dynes per square centimetre), the film could be broken by dipping a finger into the water after it had been rubbed on a person's nose. Apparently that oil from the nose had a greater spreading power than the larvicide, forcing the larvicide away from the finger and leaving it in an island of free water.

Mosquito larvae had a wax ring in the end of their tracheae which apparently acted in a similar manner to that of oil on the finger. If its spreading power was greater than that of the larvicide, it forced the oil film away from the tracheae and left the larvae free to move about in a small patch of larvicide-free water. Since the spreading agents normally used in larvicides were emulsifiers, it was theorized that their use might have been of more importance in breaking down the wax cuticle at the end of the tracheae rather than in providing spreading pressure. From that point of view of relative spreading power, it was suggested that that might be studied as a photoelastic problem in an engineering laboratory.

An added complication was that identical formulations of DDT and spreading agent in different oils having the same general specification (United States Public Health Service specification for oil used in mosquito control) often had entirely different killing powers, depending on the source of the oil. The presence or absence of impurities in those oils, even in relatively small amounts, appeared to account for those differences.

Mr Cedric Mellor said that although the Lecturer had stated that not much was known about the flight range of the *labranchiae* mosquito, it would be interesting to know if any indication could be given of the flight range of other mosquitoes.

The Lecturer, in reply, said it was believed that *labranchiae* had a flight-range of approximately 2 kilometres. In practice a figure of 3 kilometres was used, and eradication zones of that radius were established around positive *labranchiae* foci. Many entomologists had given figures on flight-range for other mosquitoes, but from a practical point of view an ever-present difficulty was that, in unusual circumstances, those could be exceeded. Cases had been reported from the Egyptian desert where wind currents had carried mosquitoes for more than 40 miles.

STRUCTURAL AND BUILDING ENGINEERING DIVISION MEETING

2 December, 1952

Professor A. J. S. Pippard, Member, Chairman of the Division, in the Chair

The following Paper was presented for discussion and, on the motion of the Chairman, the thanks of the Division were accorded to the Author.

Structural Paper No. 33

"The Design and Construction of the British European Airways Hangars at London Airport, with Particular Reference to Prestressed Concrete"

by

Dudley Holt New, B.Sc.(Eng.), M.I.C.E.

SYNOPSIS

The Paper describes the design and construction of the buildings for the British European Airway's new maintenance base at London Airport, which is one of the largest schemes on which prestressed concrete has been extensively used.

The construction of the various buildings is explained, particular attention being paid to the prestressed concrete units used in the floors and roofs.

The hangar roof is carried by Freyssinet-type beams of 110 feet clear span, made up of T-section units, 4 inches thick. These beams are carried across the 150-foot-wide main doorways on hollow rectangular Freyssinet beams, 14 feet deep with 4-inch-thick walls, stiffened by precast diaphragms, which are themselves prestressed to carry the crane beams and canopy roof.

The roof of the North Block is carried on I-section beams, prestressed on the fully bonded long-line process, while the annexe floors and roof have as their carrying members fully bonded prestressed rectangular beams, which act monolithically with strips of cast-in-situ floor to give composite T-beam construction.

Basic calculations for the main sections of the major prestressed units are given and also short descriptions of the testing carried out at the works and on site.

Introduction

The buildings described in this Paper are to house the permanent maintenance base of British European Airways, which is in the process of being moved from Northolt to London Airport. They are planned to service the two fleets of new-type aircraft owned by the Corporation—twenty de Havilland Airspeed Ambassadors (Elizabethan Class) and twenty-six Vickers Viscounts (Discovery Class), but as the new aircraft and the organization housed in the new base settle down, there is no doubt that a considerably larger number of aircraft can be based in the new building.

It will be appreciated that the financial success of operating a civil airline depends largely on keeping the aircraft in continuous service, in the same way that a civil engineering contractor must, for economy, keep his plant in constant use. Efficient maintenance is therefore a matter of primary importance.

In the past, British airways have often had to maintain their aircraft in unsuitable or improvised accommodation, resulting in high costs both in the actual maintenance operations and in the lost working time spent by aircraft on the ground. The new hangars and workshops have, therefore, been planned to afford the most efficient maintenance organization possible.

The high capital value of the machines adds to the importance of the factor of maximum use. The British European Airways engineering staff, in designing the lay-out of the base, carefully considered this factor and the nature of the operations of the airline, that is to say, the operation of short-haul services calling for a high proportion of the fleet being out and back in the day. Obviously, an efficient maintenance turn-round was a first essential to deal with the various categories of work to be done on aircraft visiting the base. Some of the more frequent maintenance tasks can be done outside on suitably sized and sited aprons, provided that workshop and stores facilities are near by, whilst more extensive maintenance calls for hangars backed by workshops and stores.

The lay-out shown in Fig. 1, Plate 1, together with external aprons on either side was, after extensive planning work, considered to be the best solution. It will be noted that there is a central roadway for the approach of vehicular and pedestrian traffic, which obviates avoidable movement of this traffic in areas used by aircraft.

It should be borne in mind that, in deciding the actual dimensions, limitations imposed by runway clearances and plans for future development of other parts of the airport had to be taken into account.

The main contract, comprising the weatherproof structural carcase of five hangars, ancillary buildings, and a repair block, with a possible addition of a further five hangars with their ancillary buildings, was the subject of a competition organized by the Ministry of Civil Aviation on behalf of British European Airways.

The competitors were required to submit a lump-sum tender based on their own structural design but conforming to the general requirements of the lay-out, sections, elevations, specifications, and conditions provided by the Ministry. Tenders were invited from specialists in both steelwork and reinforced-concrete construction. Only three months were available for the reinforced-concrete specialists to prepare the scheme, including design, quantities, and pricing.

After intensive discussions regarding principles of design, testing, and contract conditions, the successful contractor commenced his preparatory operations on the site on 10th August, 1950. In the scheme finally accepted,

which was for ten hangars, the contractors had not confined themselves to any particular medium of construction, but had carefully analysed every section of the work on its own merits, the resulting scheme being a harmonious and economic blending of reinforced concrete, end-anchored prestressed concrete, and fully bonded prestressed concrete. Structural-steel sections were used as main members for the temporary floors and for the crane beams, whilst the lightweight roofs were of aluminium decking. Since this was the contractor's scheme, it was possible to increase efficiency and economy by investigating erection problems more closely at the design stage.

The finished work consists of two series of five hangars, each 900 feet long in 180-foot bays and 110 feet wide, with ancillary buildings along the length, and joined at the end by the North Block—a workshop and stores building, 465 feet long and 100 feet wide.

The five hangars in each block, although structurally separated by weathered expansion joints, have no dividing walls between them and so provide unobstructed floor space for the full length of 900 feet.

To speed up work and reduce formwork costs the general trend of the reinforced-concrete industry is towards construction in precast units, and this contract was no exception. Its very nature invited close consideration of the technique of precasting. Repetition afforded an immediate opportunity for the fabrication of precast columns on the site and their erection in pockets in foundation blocks whilst, as will be seen later, precasting was extensively used in the roof construction.

The roof of the North Block gave ideal conditions for the use of the Hoyer system of prestressing, whilst the concrete floors of the annexes afforded an opportunity for the further development of the technique of combining precast prestressed concrete and in-situ normal reinforced concrete to act homogeneously as a composite unit.

The secondary beams over the hangar roof afforded an excellent case for applying the principles developed by Freyssinet for bridging the Marne. Complete prefabrication of the 150-foot-span main beams was also considered at one period, but eventually rejected as not being more advantageous than the method already developed, using precast diaphragms only.

Shuttering to walls generally was carried out in 2-foot-square steel panels, which were arranged to give a similar pattern everywhere to the untreated concrete surface.

The lay-out of the work is shown in Fig. 1, Plate 1, and *Figs* 2 and 3 (between pp. 24 and 25) show the outside appearance of the complete building.

Site Organization

The clients and their Consulting Engineers were represented on the site by a Resident Engineer and a Resident Surveyor, each with his staff.

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The main contractor's site organization was in the charge of a Supervising Engineer, assisted by a small staff of engineers, each responsible to him for special duties, such as concrete control, planning and progress, the checking of drawings and information before issue to the site, construction methods, setting out, etc.

The Planning and Progress Engineer produced period programmes of operations from time to time, from which detailed weekly programmes were prepared in consultation with the various foremen. These weekly programmes were discussed and confirmed or modified at meetings between the Supervising Engineer, the Planning Engineer, and the foremen, when current progress and labour requirements were also agreed and any difficulties discussed and dealt with.

The Supervising Engineer exercised direct control of the building operations through a General Foreman, with several section foremen each in charge of a section of the work, such as hangars, annexes, North Block, and precasting yard. A foreman steel fixer and a foreman concreter were responsible to the General Foreman for steelfixing and concreting over all sections, while a general trades foreman was in charge of all finishing trades and controlled the activities of subcontractors through an assistant.

The purchasing, measuring, and financial sections of the contract were controlled by a surveyor and his staff, who worked very closely with the Supervising Engineer.

A Labour Officer was responsible to the Supervising Engineer for the engagement and welfare of the workmen. Weekly meetings between the Supervising Engineer (or his representative), the Labour Officer, the Federation Steward, and, when necessary, the various trade stewards enabled both the firm and the men to put forward proposals and suggestions for improving production, or working and welfare conditions.

Early in the programme scale models were made of the main structural members to enable the foremen and men to obtain a clear idea of the form and process of construction.

The all-important matter of teamwork between the client and contractor was greatly fostered by a series of discussions held at regular intervals.

Weekly meetings between the Resident Engineer and the contractor's Supervising Engineer enabled the immediate requirements of each to be made known to the other and the current progress position considered in relation to the agreed programme.

Attendance fortnightly by representatives of the specialist subcontractors afforded the opportunity of a similar exchange of information and requirements.

Monthly meetings at the contractor's head office, attended by the consultant, architect, surveyor, and contractor afforded the opportunity

of discussing major matters affecting or likely to affect the programme of work, to determine policy, and decide on necessary action.

Site Conditions and Excavation

The original site consisted of about 1 foot of top-soil, overlying 2 feet of brickearth on gravel. Before the contractors commenced work, an average depth of 4 feet had been excavated over the whole site, filled into old borrow-pits nearby, and replaced by gravel fill consolidated in 8-inch layers. This consolidated surface material overlay a natural gravel formation extending below it for a depth of about 12 feet, underlain by blue clay.

The reinforced-concrete foundations extended to about 4 feet below the original ground level and were deepened as necessary in mass concrete to found on the natural gravel, which was capable of sustaining a working load of 4 tons per square foot. The total depth below ground level of the bottom of the excavation ranged from 4 to 7 feet.

A 10-cubic-foot-capacity back-acter was used for bulk excavation, the sides and bottoms being finally trimmed by hand. A view of an early excavation is shown in *Fig. 4* (between pp. 24 and 25). Tipping lorries, of 4 cubic yards capacity, conveyed the surplus ballast from the site, while a stock-pile was retained to adjust variations in foundation levels when laying the floors.

During the summer and late autumn of 1950, the ground stood up well without timbering but in periods of frost and heavy rain considerable planking and strutting became necessary.

The water table, which was normally 9 feet below ground level, rose to 6 feet in February 1951. This high level persisted into the summer and necessitated considerable pumping for the deepest foundations and much of the drainage work.

Concreting and Concrete Control

The aggregates, obtained from pits at Wraysbury, were stored in three stock-piles, separated into sizes $\frac{3}{4}-\frac{3}{8}$ inch, $\frac{3}{8}-\frac{3}{16}$ inch, and $\frac{3}{16}$ inch down, by sleeper walls. The supply of the coarse aggregate in two sizes was, in the Author's opinion, fully justified, since reinforced concrete of the highest quality was required.

The bulk of the concrete was mixed in a central batching plant. The overhead storage bins had a capacity of 16 tons of coarse aggregate, 8 tons of medium aggregate, and 8 tons of sand. The aggregates were raised to the bins by a swinging horizontal-boom scraper and bucket-elevator mechanism.

Cement was delivered in bulk, being immediately tipped into an open

hopper through a steel grid, and conducted from there to the main storage hopper of 70 tons capacity through worm-and-bucket-elevator mechanism.

From the hoppers, aggregates and cement flowed by gravity into weigh-batchers, from which they were finally discharged into one of the two 18/12 mixers. Water also was gauged by weight.

The mixers, which were mounted about 15 feet above ground level, discharged direct into ½-yard-capacity skips, four of which were normally carried on a lorry specially fitted for the purpose. These lorries distributed concrete to the work, where the skips either delivered it direct into barrows or were raised into position by crane before discharge. Dumpers and tipping lorries were used for distribution to floor slabs and foundations. The maximum output of the plant in one day up to June 1952 was 120 cubic yards.

In addition to the main batching plant and a few mixers for drainage work, one 10/7 mixer and weigh-batcher was used for the higher-grade concrete in the main beams over the hangar doors, and one 14/10 mixer for the precast work, which was all carried out on the site with the exception of the units for the 110-foot-span roof beams.

Most of the in-situ reinforced concrete work was vibrated by means of electrical immersion vibrators, whilst petrol-driven immersion vibrators were used in the precasting yard. The 4-inch walls of the prestressed main beams were vibrated by means of Sinex vibrators clamped to the shutters.

The walls generally were concreted in 4-foot lifts with the exception of the 4-inch walls to the main beams, which were in 2-foot lifts, whilst lifts for columns, when cast vertically, were up to 8 feet. Before concreting commenced shutters were cleaned out by means of compressed air.

Concrete control was exercised from a laboratory on the site. Weigh-gauges were checked daily, whilst grading, silt content, and other factors were checked regularly. Makers' certificates were accepted for the cement used.

Sets of four 6-inch test cubes were taken at least twice a week and tested at 7, 14, and 28 days, unless the maximum strength was reached for one of the earlier tests. The test cubes were covered with wet sacking at the point where made and when sufficiently hardened were transferred to a tank in the laboratory, thermostatically controlled at 60° F. The specified cube strengths were normally reached well before the periods laid down.

Both the slump test and the Wigmore Consistometer test were used for controlling the water/cement ratio and workability. There were wide variations in comparative results, but in the Author's opinion, experience on the site indicated that the Consistometer was worthy of consideration for site control, and might well replace the slump test on major works.

COLD-WEATHER CONCRETING

The following measures were taken at the central mixing plant :—

The plant itself was shielded from direct winds so far as practicable. A boiler was installed underneath to supply the lagged tank feeding the mixers, and hot water for radiators fixed to the sides of the aggregate storage hoppers.

Tarpaulins were placed over the stock-piles at night to protect them from frost. The distribution hoppers were felt-lagged to prevent undue loss of heat during transit.

The following measures were taken on the site :—

Steam was supplied from two boilers with a total evaporative capacity of 4,000 lb. of steam per hour, located near the south end of the west hangar.

A 2-inch steam pipe ran underground from the boilers to the most south-westerly pylon, where it was carried up vertically and along the main beams, the whole length being heavily lagged. This main supplied steam for use in the west hangar. The west annexe was supplied from a further 2-inch main which ran underground to the end of the central row of columns, where it rose vertically and turned to the horizontal again, just below the first-floor beams.

Tee-pieces and valves enabled steam to be drawn from these mains through $\frac{3}{4}$-inch-diameter three-ply rubber steam-hose, from which it was distributed through $\frac{3}{4}$-inch-diameter sparge pipes with holes at about 18-inch centres.

Walls, beams, and columns were protected from frost by attaching sparge pipes to the outer faces of the shutters and draping them with tarpaulins. Floor slabs were protected by inserting sparge pipes in a 12-inch space between the slab and a protective tarpaulin over.

Service pits were heated by dropping sparge pipes into the pits and covering over with tarpaulins. The total time of steaming was in each case about 48 hours.

The Author estimates that frost precautions taken from the end of October 1951 to early April 1952 saved about 8 weeks of working time, of which 4 could be attributed to site steaming.

STEEL FIXING

All reinforcement was delivered to Feltham by rail and thence to the site by road, where it was unloaded either by hand or by means of a 2-ton mobile crane. It was supplied in random lengths and stacked on the ground in its various diameters.

Cutting was by bolt cropper or oxy-acetylene flame. One powered bending machine and two hand-operated machines were employed. Steel

was distributed round the site by means of a small mechanical horse and trolley, and hoisted to the required level by rope-and-pulley mechanism.

The fixing was normal and did not present any unusual problems. Since the bars were supplied in random lengths some welding had to be done, in order to economize in the tonnage used.

Prestressing Cables

The high-tensile 0·2-inch-diameter wire used for site prestressing was delivered in pre-straightened coils of 8 feet diameter, weighing about 3 cwt each and containing about 3,360 feet of wire. For the purpose of running out wire for cable making, twelve of these coils were assembled on a horizontal spool, seen behind the cable bench in *Fig. 5* (between pp. 24 and 25), which could turn freely when the ends of the wires were pulled, but was damped against overrun.

Twelve wires were assembled into a cable on a bench 12 feet long with a twelve-hole die at one end. The wires were passed through this die, their ends being then brought together and welded. After welding the cable thus formed was pulled out by a winch until sufficient wire had come off the spools to give the required length, before cutting and welding the other end. Cables were bound at intervals with binding wire or tape.

In the early stages a standard Freyssinet wire spiral was included in the centre of each cable but its use was eventually discontinued since it did not appear to serve any essential purpose. The cables were distributed to their working positions by hand.

Hangars

As can be seen from the artist's impression, *Fig. 2*, and the aerial view, *Fig. 6*, the front elevation of the hangars presents a series of pylons 30 feet wide. These pylons consist of two columns each 5 feet 3 inches by 2 feet 6 inches, joined by two 4-inch-thick reinforced-concrete walls with a load-carrying 12-inch-thick vertical rib midway between. Further reinforced-concrete walls form recesses 9 feet wide and 14 feet 9 inches long for housing the folding doors when in their retracted position. Plans of the pylons can be seen in Fig. 1, Plate 1, and a side view in *Fig. 7* (between pp. 24 and 25).

Rainwater pipes and other services are carried down inside the pylons. The two at the extreme north end contain access stairs to the roof and the cranes, which are normally reached by means of cat ladders. The two at the extreme south end each incorporate a feature 16 feet square which also gives access to the roof and may eventually be used as a store.

The load from the main beams is transmitted to the two pylon columns through fabricated mild-steel bearing plates. One column is rigidly fixed to the 4-inch walls, whilst the other is free to flex about its base and so

accommodate any changes in length of the main beams, and thus forms part of the expansion-joint system.

The back wall of the hangar which separates it from the annexe is in 6-inch reinforced concrete, buttressed by 2-foot-9-inch-by-2-foot columns at 30-foot centres with intermediate 15-inch-by-12-inch columns supporting the roof of the annexe. Openings in the wall accommodate automatic fire-resisting roller-type steel shutters on the hangar face and sliding steel or teak doors on the annexe or north-block faces. The main columns carry reinforced-concrete beams, 3 feet 6 inches by 2 feet 9 inches, which in turn carry the secondary roof-beams. The columns also carry the steel crane-girders on concrete brackets.

The south end wall of the hangar is in 5-inch-thick reinforced concrete, faced inside with a 1-inch-thick wood-wool insulation layer, used as shuttering and left in position. About 21 per cent of this area is glazed. The wall is stiffened by columns cantilevering from their bases and completely free at the top, vertical and horizontal movement being allowed for between the wall and the end secondary beam. It was found necessary to increase the size of these columns beyond that needed for economic strength considerations alone, in order to reduce the horizontal movement at the top induced by wind pressure. The gap between the end wall and the end secondary beam was made $2\frac{1}{2}$ inches, on the basis of 1 inch for expansion and 1·33 inch for wind deflexion, assuming a value of E for the concrete of 3,000,000 lb. per square inch.

The 6-inch reinforced-concrete north wall of the hangar, seen in the background of *Fig. 8* (between pp. 24 and 25), is structurally part of the north-block construction, and is isolated from the hangar by an expansion joint.

In the case of the rear wall of the hangar, the walls to the north block, and the annexe wall, columns were constructed in advance of wall panels with short wing-walls on each side. The greatest accuracy could thus be concentrated on the columns, the standard panel shutters merely following the profiles already set up.

The shuttering for the rear wall of the west hangar was fixed by means of a fabricated steel frame, 100 feet long and 60 feet high, supported on three rows of wheels at 6-foot centres running on concrete beds. The shuttering for both columns and walls was rigidly fixed to members of the frame, handling being facilitated by the use of chain blocks and tackle hung from the frame. The shuttering was cleaned between lifts, without removal from the structure, and when the frame was winched forward to a new position, a matter which took only a few hours, the shuttering still remained within the frame, reducing handling to the minimum.

Hangars—Main Beams

The 14-foot-deep beams over the main openings, details of which are given in Figs 9, Plate 1, are of 150 feet clear span. Their end

reactions are transmitted to the supports through steel end bearings, and to ensure that no movement can take place between the two parts of these bearings and to assist with eccentric loading two Freyssinet cables pass through them from the column and are anchored in the lower portion of the beam.

The soffit shuttering to the main beams was supported by either military trestling as shown in *Fig. 10* or by five structural steel towers mounted on wheels for ease of movement, the weight being finally transmitted to the ground by means of four bottle-jacks. The soffit shuttering itself consisted of two lines of 2-foot-square units with a make-up strip between, carried on longitudinals bearing on transverse timbers, carried on the towers, and set to levels to give the required camber.

A series of precast diaphragms and end-anchorage blocks were erected on the beam soffits (*Fig. 10*). These precast concrete diaphragms at 15-foot centres are located so that they each take a direct load from a 110-foot-span secondary beam. They each contain two Freyssinet cables reinforcing the crane bracket on the inside and the canopy bracket on the outside.

The canopy is roofed with Bison prestressed units covered with two layers of felt, while the front elevation is formed of ribbed precast concrete fascia units (*Fig. 7*). The canopy brackets also accommodate the top housing of the electrically operated " Esavian " folding doors. The ceiling of the canopy is finished in rendered Hy-rib.

After the diaphragms were in position and exactly located by means of a grid of scaffold tubes or a steel framework, the next operation was to place the cable sheathing, which was formed of a close-jointed conduit, spot welded at intervals of about 12 inches.

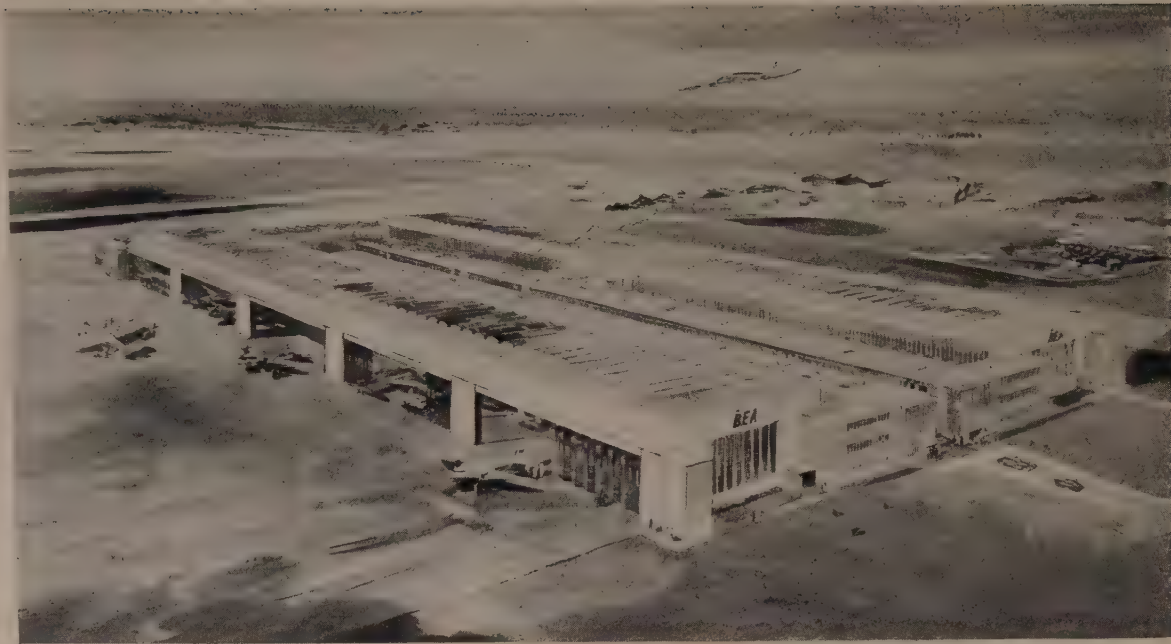
The sheathing was placed by threading it through the holes in the diaphragms, the joints between the various lengths being just outside the vertical faces thereof. As the cables left the centre sections the outer groups were swept upwards into the walls, while others were bent outwards in the bottom to take their place, and swept upwards in turn. At the support sections there were seven cables in the bottom flange and seventeen in each web, giving a well distributed anchorage pattern.

The sheaths were located in their exact positions by suspending two steel rods per bay from a scaffold tube over, the rods being hooked round the tube and the hooks finally cast into the top slab. The rods are near the inside face of each 4-inch wall, and located in relation to it by means of concrete distance-pieces. The sheaths were positioned exactly and then tied to the suspended rods.

The cables, which were about 175 feet long and weighed about 2 cwt each, were manhandled from the cable-making yard where they were stored in straight lengths. They were pulled into the sheaths in the following way.

A pilot wire consisting of a single prestressing wire with a hook on the end was first pushed through the whole length of a sheath, and a wire

Fig. 2.



Artist's Impression of Completed Hangars

Fig. 3

Exterior of Finished Hangar

Fig. 4

Typical Excavation Work for the Foundations

Fig. 5

Cable Bench and Horizontal Spool

Fig. 6

Aerial Photograph, June 1952

Fig. 7

North-West Pylon showing Canopy Construction and Recess for Sliding Doors

Fig. 8

Interior of a Finished Hangar

Fig. 10

ERECTION OF DIAPHRAGMS FOR MAIN BEAM

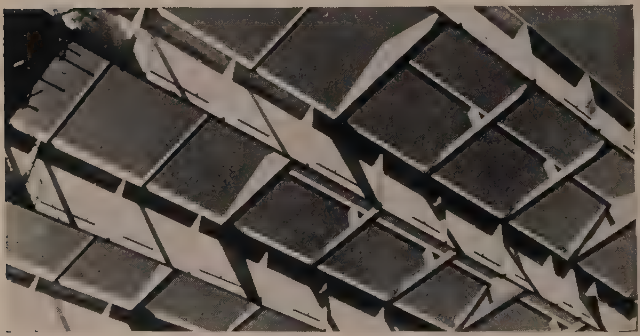
Fig. 11

MANOEUVRING A SECONDARY BEAM ON BOGIES AND TRACK

Fig. 12

Erection of a 110-foot-span Roof Beam

Fig. 13



Skeleton of the Hangar Roof

Fig. 14

Hangar Roof nearing Completion

Fig. 16

I-section Beams on the Prestressing Bed, North Block

Fig. 17

Prestressed Roof Beam Arrangement, North Block

Fig. 19

PRESTRESSED BEAMS AWAITING FLOOR MEMBERS, WEST ANNEXE

Fig. 20

COMPOSITE FLOOR WITH IN-SITU TEE (HANGAR BEAMS BEHIND), WEST ANNEXE

rope attached to the end, which was then pulled through and the pilot wire removed. For the first beam the cables were pulled up with the assistance of the wire rope, over a gentle curve formed of scaffold tubes, and then through the sheaths by means of a winch connected to the rope. On later beams, the cables were laid out in position on the top of the one behind before being attached to the wire rope and pulled through. Cables varied in length and were marked with brass tabs indicating their position in the beam.

When all the cables were in position and the bottom slab had been cast, horizontal surfaces were formed on the outer timber longitudinals by means of timber fillets to give a level bearing for the bottoms of the series of 2-foot-square panels which formed the shuttering to the sides. The side walls were concreted in lifts of 2 feet since there was little clearance round the prestressing cables and dense concrete was absolutely necessary. The top-slab formwork was made up of steel decking panels carried on bearers at 2-foot centres supported on runners bolted to the vertical walls. Prestressing was normally carried out 14 days after the last concrete had been cast.

A $1:1\frac{3}{4}$ cement-sand grout was finally applied from one end under a pressure of 80 lb. per square inch. When this appeared at the other end, the hole was plugged with a wooden plug, with the pressure still on, the pressure then immediately being released and a plug similarly inserted at the grouting end.

The final operation, after the secondary beams had been placed and all the cables had been stressed, was the casting of the concrete cover slab to the ends of the Freyssinet cones.

Hangars—Secondary Beams and Roof Construction

The secondary beams span 110 feet clear between the longitudinal beams on either side and are made up of precast T-section units and end blocks.

The T-section units, which are 6 feet deep and 3 feet wide, have 4-inch-thick webs and flanges stiffened at one end with a concrete diaphragm; they are reinforced with mild steel in the web for handling and in the table of the tee for roof loading. All the units, including the end blocks, were precast at a nearby works and delivered to the site by road.

The units were cast with the stiffening rib uppermost, in timber shutters lined with asbestos sheet, and since the holes for the cables were all straight in a particular unit, although varying from unit to unit as can be seen by reference to Figs 9, Plate 1, they were formed by means of bright-steel rods located by jigs at each end, the rods being withdrawn as soon as the concrete had just set. The cable holes were thus unlined and comprised a series of short straight chords with slight changes in direction between the units.

The exact position of the cable holes was modified to allow for service holes with a negligible effect on stresses.

Each unit was cast in one operation, under external vibration, the shutters being normally removed and the units handled after a period of about 24 hours had elapsed. A rigid system of inspection was carried out at the works, before unloading on site, and during construction.

The units were assembled into beams on the gravel floor of the hangar area, mass-concrete bearers being laid on a blinded surface at each end to support the end blocks, while one end block was further supported on rollers to allow free movement under stressing. The intermediate T-sections were supported on timber bearers to the required line and level and propped from the sides.

The units were positioned with gaps of ¾ inch between, metal thimbles crossing these gaps to protect the cables during packing of the joints. When all the units in a beam had been correctly aligned and levelled and the eight Freyssinet cables threaded through by pushing from one end, the joints were packed with hard-driven dry 1 : 1½ cement-sand mortar.

The cables were stressed by Freyssinet jacks from both ends 24 hours or more after completion of the dry packing, and grouting was carried out a few days later.

Finally the projecting wires were trimmed from the ends of the cables and the recesses in the end blocks filled with mortar. The completed beams, each weighing about 26 tons, were not normally moved until 7 days after prestressing.

For erection, the ends were lifted by a mobile crane on to bogies running on tracks (*Fig. 11*, between pp. 24 and 25) and by this means manoeuvred into a position from where they could be raised by a guyed lifting mast (*Fig. 12*) and placed in their final location, a new position of the mast being required for each beam. Holes were provided in the end blocks to enable their attachment through steel links to the ends of the steel lifting beam (*Fig. 11*). This allowed the whole beam to be picked up from the ends only and thus the dead-weight bending moment, which was taken into account in the design, was constantly in operation.

Generally it was found possible to position the two ends of each beam accurately and immediately. However, some of the first beams were a few inches out of position, but it was found to be a simple matter to jack these back into their correct position by bearing against two others.

Figs 9, Plate 1, shows the arrangement at the end bearings. The ends of the secondary beams were first bedded down on two mild-steel plates, with mortar between, and when in position, the bearing was finished with dry-packed mortar.

A strip, 25 feet wide, on either side of the roof is covered with aluminium interlocking decking with insulating board and bituminous felt finish, carried on prestressed concrete purlins. The remainder of the portion of the roof between the beam tees is glazed, each section of glazing being

carried on two shaped precast end units, four precast carrying units with central stub columns, and a central precast unit from which splice bars protrude into the space between at each secondary beam. This space is filled with in-situ concrete, thus completing a central member which runs the whole length of each hangar and stiffens the flanges of the secondary beams. These items can be clearly seen by reference to Figs 9, Plate 1.

Precast units were erected by means of a small derrick fixed to the secondary beams. Tees of the prestressed beams were provided with precast concrete kerbs bolted to each side, which formed rainwater channels and edges to the lantern lights.

The weight of steel in the roof structure, including 110-foot-span beams but excluding their supports, is $17\frac{1}{2}$ lb. per square yard.

Erection of the deluge and electric-light fittings was carried out from a scaffold board and tube platform suspended from eye-bolts attached to the beams. The eye-bolts have been left in position so that maintenance work will be facilitated at some later date.

The Author feels that the slim lines of the 4-inch webs of the T-beams shown in *Fig. 13* (between pp. 24 and 25) were a contribution to modern architecture, and it is with regret that he calls attention to *Fig. 14* which shows that these lines have been substantially obscured by the strip-lighting fittings, attached to the bottoms of the beams.

North Block

The North Block (Fig. 15, Plate 2) is 465 feet long and 100 feet wide and contains a central row of columns 24 inches by 18 inches, at 42-foot-3-inch centres. The walls generally are of 5-inch-thick reinforced concrete with 1-inch wood-wool lining internally, except that they are 6-inch-solid concrete where they abut the hangars and annexes.

The whole of the block is of single-storey construction with the exception of an area which has a temporary floor made up of structural steelwork and Bison precast units. Provision has been made in the vicinity of this floor for extension by allowing for future openings in the walls 41 feet wide, the temporary walls in this position being formed of two 3-inch-thick skins of foam-slag blocks with a 2-inch cavity between. The end walls of the block are buttressed by columns which span for wind reactions between the ground and the roof.

The central row of columns carries the temporary floor and the crane girders on brackets. The top extremity of the columns is 15 inches wide and 2 feet 6 inches long and accommodates the main beams which bear for a distance 6 inches from each side on a mortar bed. A space is thus formed above the columns into which extend mild-steel reinforcing bars from them and the main beams. This space is eventually filled with in-situ concrete. Further bars extend upwards to connect with the space between the secondary beams above.

The construction of the columns and of similar columns in the annexe was accelerated by the use of wheeled mobile scaffold towers, 10 feet square and 30 feet high. The column boxes which were located by these towers were 12 feet high with one side constructed in two 6-foot lifts. They were made of timber, lined with resin-bonded asbestos board.

The main beams, which are of I section, 45 inches deep and 12 inches wide, weighing 7 tons each, run centrally from end to end of the block. They were precast and prestressed by the " fully bonded long line " process as indicated in *Fig. 16* (between pp. 24 and 25), being delivered to the site by road and lifted into position by means of a tracked crane.

The precast prestressed secondary roof beams at 14 feet centres are of I section 27 inches by 12 inches, and 50 feet long, each weighing 5 tons. They were manufactured, delivered, and erected in a manner similar to the main beams. They rest at one end on the column extensions or the main beams and at the other on the wall columns, except over the future openings where they are carried on normal reinforced-concrete beams. They are held in position by protruding mild-steel reinforcement at the ends, which is eventually surrounded with cast-in-situ concrete in a manner similar to the joints between the main beams.

Rectangular (9 inches by 4 inches) prestressed precast concrete purlins, notched at the ends, span between the secondary beams and carry the light metal decking and small water tanks. The patent metal glazing is carried by normal reinforced-concrete members. The weight of steel in the roof structure, excluding supports and the 45-inch-by-12-inch central beams, is $12\frac{1}{4}$ lb. per square yard. The arrangement of normal precast concrete roof members is shown in *Fig. 17* (between pp. 24 and 25).

There is an expansion joint at about the centre of the block which is made up in the following manner.

The 5-inch-thick wall is stopped off vertically at one side of the column face and increased in thickness to 12 inches for a distance of 8 inches. A nib on the column face fits into a recess in the wall, thus allowing free expansion movement while maintaining stability at the end of the wall. The joint is weathered by a copper expansion-strip. Movement in the main beams is allowed for by one end of a beam being free to move on its column bracket support through a steel-to-bronze bearing, treated with graphite grease. Movement of the purlins, which are normally fixed to the secondary beams by means of a rag bolt and cover plate, is allowed for by coating the bearing face of one end of the purlin with bitumen before placing it on its mortar bed. The cover plate in this case, instead of bearing hard on the top of the purlin, is cranked up to miss it and holds in position an enclosing steel strap, which is isolated from the purlin through bitumastic felt packing and allows free longitudinal movement but prevents any transverse displacement.

Annexes

The annexe walls are generally in 5-inch-thick reinforced concrete with a 1-inch wood-wool lining, but 6 inches thick without lining where they abut the hangars and enclose an inflammable store. The walls are buttressed with columns at 15-foot centres. (See *Fig. 18*, p. 30.)

The width of the annexe varies, being either one or two bays each 40 feet wide; the bays are of different heights. The columns are designed as free cantilevers fixed in their bases. Brackets on the columns carry the main floor and roof beams. All the internal columns were at first cast in situ but in order to speed up the work some of them were eventually precast horizontally on the site then set in prepared slots in their foundation blocks. Columns in the external walls were concreted with small wing walls on either side with protruding steel for lapping with the main steel structure and taken up in advance of the walls. Wall shutters were made up in steel panels 4 feet deep, braced with scaffold tubes, the shuttering being bolted through the column wing walls at each end. The complete shutter units were in all cases handled by means of chain blocks and tackle fixed to the scaffold over.

Certain portions of the floor and roof are necessarily of in-situ reinforced concrete, but the bulk of the work has a large repetition factor and is constructed in composite T-beam construction.

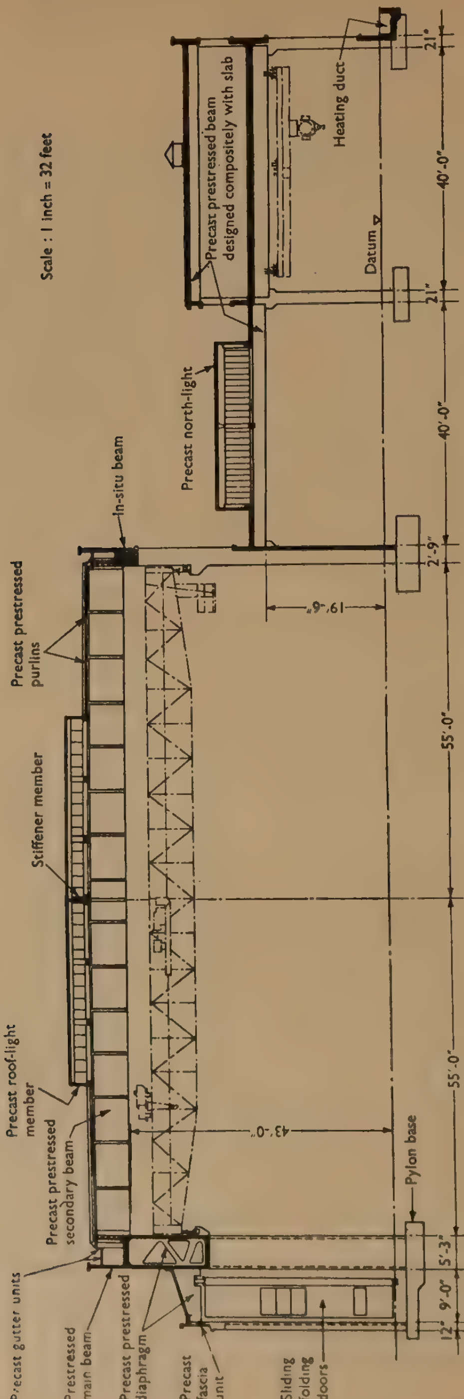
The rectangular lower portions of the T-beams are precast and prestressed on the " fully bonded long line " process. The sizes generally are 34 inches by 12 inches and 21 inches by 12 inches, the units weighing 8½ tons and 5 tons respectively. The units were manufactured with lifting eyes near the ends and placed in position by means of a crane mounted on crawler tracks.

In order to reduce the headroom the T-beams were designed to be propped at third points during construction, by means of towers made up of tubular steel scaffolding. The ends of the rectangular portions of the beams were stopped back (*Fig. 19*, facing p. 25), to give spaces adjacent to the columns into which bars from the columns and the ends of the beams could protrude, the joint being finally made with in-situ concrete.

The floors and roof of the west annexe are of Triad floor units positioned to rest on the edges of the beams, concrete floor pots being placed between them near the centre of their spans and solid slabs adjacent to the beams. Portions of the floor above the solid slabs and immediately adjacent to the beams were then cast in in-situ concrete to give a T-section to act monolithically with the prestressed portion of the beam, as shown in *Fig. 20* (facing p. 25).

Owing to the acute steel shortage which existed in the winter of 1951/52, it was decided to carry out the floors and roof of the east hangar in prestressed joists of a type known as " X " joists; floor pots, slabs, and placing of in-situ tees followed the same pattern as before. This

Fig. 18



TYPICAL SECTION THROUGH WEST HANGAR AND ANNEXE

alteration meant a saving in initial dead weight of about 20 lb. per square foot on the floors and 10 on the roofs. By a slight modification in design it was then possible, in certain cases, either to dispense with propping or to use one central prop only.

The north-light roofs were made up of a series of normal precast units, erected on the prestressed beams as shown in Figs 21, Plate 2.

Design

Normal Reinforced Concrete

The beams, slabs, and columns were designed generally in accordance with C.P. 114 (1948). Wind was allowed for in accordance with Chapter 5 (Loading) C.P. 3, *P* being taken as 25 lb. per square foot for hangars and 20 lb. per square foot for other buildings.

The columns generally were taken as completely fixed in their bases, any connexion with beams over being for location only and without continuity.

The calculations for the pylon bases were extensive but straightforward, and considerable investigation was necessary before the maximum effects of loading could be determined.

The actual stresses used for the concrete were 1,100 lb. per square inch in bending plus 365 lb. per square inch for wind effects only; and 836 lb. per square inch for direct stress. The minimum works cube strength specified was 3,300 lb. per square inch at 28 days.

Fully Bonded Prestressed Concrete Beams (*Hoyer*)

All beams were designed as simply supported and reinforced with 2-millimetre-diameter wires running straight from end to end, thus inducing the same prestress at all similar sections on the beam.

The concrete stresses used were :—

Compressive bending stress and effective prestress	2,500 lb./sq. in.
Prestress at moment of release	2,900 ,,
Allowable tensile bending stress	250 ,,
Allowable average shear stress without prestress relief	250 ,,
6-in. cube strength at 28 days	8,800 ,,
6-in. cube strength at release	5,500 ,,
Initial wire stress (The wires are overstressed by 10 per per cent and held thus for 2 minutes to eliminate the effects of creep)	92 tons/sq. in.
Effective wire stresses	79½ tons/sq. in.
Breaking stresses	140 ,,

0·1-per-cent proof stress was to be 98 tons per square inch. Its normal

value was 110 tons per square inch. The Modular Ratio m was taken as 11.

End-Anchored Prestressed Concrete Beams (*Freyssinet*)

Compressive bending stress	2,000 lb./sq. in.
Tensile bending stress	200 ,,
Principal tensile stress at section of maximum shear	150 ,,
6-in. cube strength at 14 days (at which strength stressing could be carried out)	6,000 ,,

Steel

Maximum stress under prestressing	77·5 tons/sq. in.
Effective stress in steel after allowing for all losses	66 ,,

(giving a final effective cable load on a 12-wire cable of 55,000 lb.; 54,000 was used for the 110-foot-span beam).

Periodic tests were made on the wire and the ultimate tensile strength was normally about 108 tons per square inch. The maximum 0·1-per-cent proof stress was to be 77 tons per square inch, but this was normally more than 90 tons per square inch. The Modular Ratio m was taken as 8.

A few typical calculations for the prestressed work are given below :—

North Block—Roof Purlins (*Fig.* 22, p. 34)

Max. moment due to dead weight, services, and live load of 30 lb./sq. ft.		113,000 lb.-inches
Max. upward bending moment due to dead weight, services, and an upward wind of 1·2P		28,200 ,,
Maximum end reaction		2,650 lb.
Number of wires		52
Equivalent concrete-area of section		38·6 sq. inches
Centroid of wires, height above soffit		3·35 inches
Centroid of combined section, height above soffit		4·43 ,,
Second moment of area		249 inches^4
Section moduli :—Top		54·4 inches^3
Bottom		56·2 inches^3
Effective prestress :—Top	1,170 − 895 =	275 lb./sq. in.
Bottom	1,170 + 867 =	2,037 ,,
Stresses due to max. movement downward :—		
Compression		2,070 ,,
Tension		2,000 ,,

Stresses due to wind moment upwards :—	
Tension in the top	518 lb./sq. in.
Compression in the bottom	500 ,,
Totals :—	
Extreme stresses in the top :—	
Tension	243 ,,
Compression	2,345 ,,
Extreme stresses in the bottom :—	
Min. compression	37 ,,
Max. compression	2,537 ,,

Here the Author would point out that, since it has been found by experience that units can be quite safely handled with induced tensile stresses of from 400–450 lb. per square inch, he considers that it would have been reasonable to allow a working stress of 400 lb. per square inch tension for the high wind-values used, instead of the 250 lb. per square inch specified.

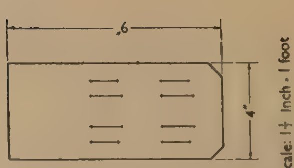
North Block—50-foot-span Roof Beams (*Fig. 23*, p. 34)

Maximum bending moment	3,079,000 lb.-inches
Maximum end reaction	14,900 lb.
Area of concrete section	205 sq. inches
Area of steel (316 wires)	1·58 ,,
Equivalent concrete area ($m = 11$)	15·8 ,,
Centroid of wires, height above the beam soffit	7·45 inches
Centroid of combined section, height above soffit	13·05 ,,
Second moment of area of combined section	17,880 inches^4
Section moduli :—Top	1,280 inches^3
Bottom	1,370 inches^3
Effective prestress (after shrinkage and creep) :—Top	40 lb./sq. in.
Bottom	2,360 ,,
Resultant stresses under full load :—	
Compression in top	2,450 lb./sq. in.
Compression in bottom	110 ,,

The 27-inch-by-12-inch beam, which is equivalent in strength to a 20-inch-by-6½-inch R.S.J. (65 lb. per foot) contains 8·5 lb. of steel per foot run, giving a steel ratio of 1 : 7·7.

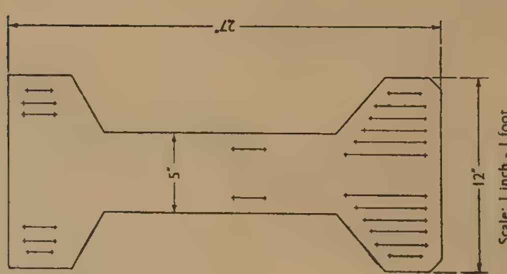
The 45-inch-by-12-inch I beam contains 17·25 lb. of steel per foot and is equivalent to a compound steel girder comprising a 24-inch-by-7½-inch R.S.J. with two 12-inch-by-½-inch plates (total weight, 134½ lb. per foot), giving a steel ratio of 1 : 8·4.

Fig. 22



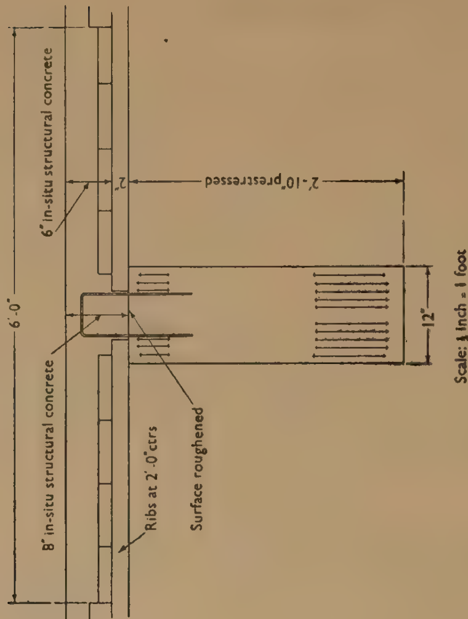
TYPICAL SECTION OF ROOF PURLIN

Fig. 23



TYPICAL SECTION OF 50-FOOT-SPAN MAIN ROOF BEAMS, NORTH BLOCK

Fig. 24



TYPICAL SECTION OF COMPOSITE FLOOR BEAM

Annexes—Composite Floor Beam (Fig. 24)

Maximum moment (dead and live)		11,286,000 lb.-inches
End reaction		102,760 lb.
Number of wires		630
Equivalent area of prestressed section		439·5 sq. inches
Centroid of steel, height above soffit		11·21 inches
Centroid of combined section, height above soffit		16·6 ,,
Second moment of area		41,400 inches^4
Section moduli :—Top		2,370 inches^3
Bottom		2,490 inches^3
Effective prestress :—Top	1,250 — 1,250 =	0
Bottom	1,250 + 1,180 =	2,430 lb./sq. in.
Centroid of composite section (neglecting wires), height above soffit		28·5 inches
Second moment of area of plain concrete section		143,000 inches^4
Section moduli :—Top		10,600 inches^3
Bottom		5,020 inches^3

Then, if the beam is propped until the table of the tee has sufficiently matured, the bending stresses are :—

Top	1,060 lb./sq. in.
Bottom (including 200 lb./sq. inch for shrinkage)	2,450 ,,
Taking wires into account :—	
Centroid of composite section, height above soffit	27·8 inches
Second moment of area	152,000 inches^4
Section moduli :—Top	10,700 inches^3
Bottom	5,470 inches^3
Resultant stresses :—Top	1,052 lb./sq. in.
Bottom (including shrinkage)	2,260 ,,

Calculations were made at intermediate stages in order to cut down the width of the cast-in-situ tee, which in turn reduced horizontal shear effects.

The Author would emphasize that he does not consider it good practice to form the tee of the same high-quality concrete as the prestressed beam, because this is wasteful of cement, increases shrinkage effects, and serves no useful purpose.

The following approximate figures show the effect if the value of *E* for the tee is two-thirds of the prestressed-beam value. Then the equivalent width of top slab is 48 inches and, taking the effect of wires into account.—

Height of centroid of equivalent section above soffit		25·8 inches
Second moment of area		130,764 inches^4
Section moduli :—Top		8,070 inches^3
Bottom		5,060 inches^3
Resultant stresses :—Top	$\frac{2}{3} \times 1,380 =$	930 lb./sq. in.
Bottom	2,230 + 200 (shrinkage) = 2,430	,,

In the design of composite beams it is always necessary to weigh the advantages of reduced beam depth against ease of construction. In this instance, for ease of construction, it would have been better to omit the props and design the prestressed portion to carry the majority of the dead load, without assistance from the tee. This would have necessitated an increase in depth of the beam of 7 inches and, owing to restricted head-room, resulted in an all-round increase in the building height.

150-foot-clear-span Main Beams

The following calculations refer to the central section :—

Bending moment due to weight of beam only	84,400,000 lb.-inches
Bending moment due to secondary beams, roofing, crane beams, and fascia beam	133,600,000 ,,
Bending moment due to live loads and cranes	73,600,000 ,,
Bending moment due to wind, upwards	58,200,000 ,,
Centroid of concrete section, height above soffit	91·5 inches
Centroid of steel, height above soffit	2·75 ,,
Area of concrete section	2,035 sq. inches
Number of cables (Freyssinet type, 12 wires, 0·2 in. dia.)	41
Second moment of area of concrete section	7,528,000 inches^4
Section moduli :—Top	98,400 inches^3
Bottom	82,300 inches^3

Thirty-three cables were stressed in the first operation, the remaining eight being stressed when the secondary beams were in position.

The stresses due to cable effects only are as follows :—

Tension in top (33 cables)	750 lb./sq. in.
Tension in top (41 cables)	930 lb./sq. in.
Compression in bottom (33 cables)	2,850 lb./sq. in.
Compression in bottom (41 cables)	3,550 lb./sq. in.

The resultant stresses with thirty-three cables and without secondary beams are as follows.

Compression in top	$- 750 + 860 =$	110 lb./sq. in.
Compression in bottom	$+ 2{,}850 - 1{,}020 =$	1,830 ,,

The resultant stresses with forty-one cables and all dead load are as follows :—

Compression in top $- 930 + 860 + 1{,}350 = 1{,}280$ lb./sq. in.
Compression in bottom
$+ 3{,}550 - 1{,}020 - 1{,}620 = 910$,,

Live loads and crane loads will increase the stresses to * :—

Compression in top	$1{,}280 + 745(715) =$	2,025(1,995) lb./sq. in.
Compression in bottom	$910 - 890(770) =$	20 (140) lb./sq. in.

The resultant stresses with maximum upward wind load combined with dead loads only are :—

Compression in top	$1{,}280 - 590(570) =$	690 (710) lb./sq. in.
Compression in bottom	$910 + 710(610) =$	1,620(1,520) lb./sq. in.

Some of the cables were passed from the bottom slab to the side walls, and inclined towards the end, being actually used to form a cantilever at one end.

The combined stresses at various sections were checked in a similar manner to those at the central section.

Effects of direct shear, torque, wind drag on the roof, and side wind loading were investigated, but not found to cause stresses that called for any modification of the section, or additional mild steel.

The total weight of steel in one beam is 7¼ tons.

110-foot-clear-span Secondary Beams (Figs 9, Plate 1)

The following calculations refer to the central section :—

Bending moment due to weight of beam only	9,000,000 lb.-inches
Bending moment due to remainder of dead load	4,950,000 ,,
Bending moment due to live load	5,320,000 ,,
Bending moment due to wind, upwards	7,130,000 ,,
Number of cables (Freyssinet type, 12 wires, 0·2-in. dia.)	8
Centroid of concrete section, height above soffit	47·3 inches
Centroid of cables, height above soffit	14 ,,
Area of concrete section	406 sq. inches
Second moment of area of concrete section	216,420 inches^4

* Cable holes will now be grouted and the figures in parentheses denote the stress if full bond is assumed. Modular ratio, $m = 8$.

Section moduli :—Top 8,780 inches^3
Bottom 4,580 inches^3

Stresses due to effect of cables only (cable load, 54,000 lb.) :—

Tension in top 1,060 — 1,640 = 580 lb./sq. in.
Compression in bottom 1,060 + 3,140 = 4,200 „

These stresses are relieved by the effect of the moment due to the self-weight of the beam, which acts as soon as the beam lifts off the shuttering under the action of the prestressing forces. The stresses will then be :—

Compression in top — 580 + 1,025 = 445 lb./sq. in.
Compression in bottom + 4,200 — 1,875 = 2,325 „

When the beam is in position and the dead load of the roof is acting, the stresses will be * :—

Compression in top + 445 + 565(530) = 1,010(975) lb./sq. in.
Compression in bottom 2,325 — 1,080(890) = 1,245(1,435) lb./sq. in.

and with the further addition of the live load :—

Compression in top 1,010(975) + 605(575) = 1,615(1,550) lb./sq. in.
Compression in bottom
1,245(1,435) — 1,160(960) = 85(475) lb./sq. in.

The maximum stresses due to wind uplift will be :—

Compression in top 1,010(975) — 810(770) = 200(205) lb./sq. in.
Compression in bottom
1,245(1,435) + 1,555(1,280) = 2,800(2,715) lb./sq. in.

As can be seen from Figs 9, Plate 1, the cables were inclined towards the ends, and the combined efforts of bending and prestressing were analysed at various sections.

The beams were also examined for the effects of direct shear, torsion, and wind drag, but none of the stresses set up were found to be of consequence.

The total weight of steel in one beam is 1·2 ton.

Testing of Beams

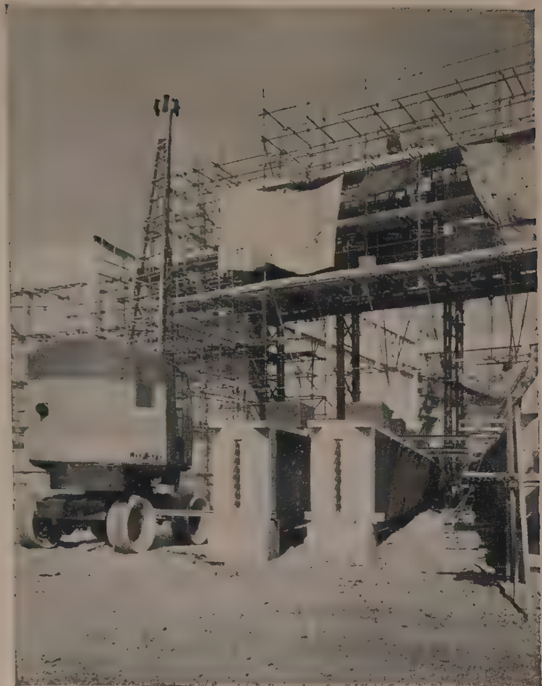
Specimens of all prestressed beams were tested, the largest when actually incorporated in the work.

110-foot-clear-span Freyssinet Beams

Two beams were set up on concrete end blocks as shown in *Fig. 25* and braced together to simulate their working condition when stayed by the purlins, roof-light members, and central stiffener.

* Cable holes will now be grouted and the figures in parentheses denote the stress if full bond is assumed. Modular ratio, $m = 8$.

Fig. 25



Test Load on a Pair of 110-foot-span Hangar Beams

Fig. 26

Failure of a Secondary Beam under Prestress

Fig. 27

TEST LOAD ON THE FIRST 150-FOOT-SPAN HANGAR BEAM

Fig. 28

TESTING A PAIR OF ANNEXE BEAMS IN OPPOSITION

The total test load placed on each beam was 24 tons, in the form of 3-ton cast-iron blocks placed in position by crane. The maximum deflexions at the centres of the two beams were 1·51 and 1·625 inch respectively. The residual deflexion after the load had been removed was not more than $\frac{1}{16}$ inch. These deflexions gave a calculated value of E for the concrete of about $5{\cdot}2 \times 10^6$ lb. per square inch.

One claim advanced for prestressed concrete is that it has an "automatic" safety factor, in that faulty materials or workmanship will be shown up under the prestress, which is normally the highest stress to which any member will be subjected.

The strength of this claim was clearly illustrated by an incident which occurred during the construction of the secondary beams soon after the test loading had been carried out. About 12 hours after prestressing, and 36 hours after packing the joints, the cableways in a completed beam were being flushed with water with the object of achieving a more efficient grout injection. Just after the completion of this flushing there was a failure at the junction of two units which is illustrated in *Fig. 26*.

This failure was closely investigated by all concerned and the Road Research Laboratory compared the quality of the concrete in the damaged units and similar units of the beam which had not failed, by the ultrasonic-pulse technique, but could find no significant differences. They also cut from the damaged members 4-inch cubes which were tested in direct compression. The strength records showed that the concrete should have satisfactorily withstood the prestress load.

There was insufficient evidence to define exactly the cause of the failure and since there appeared to be no reason why further trouble should be anticipated, work proceeded on the manufacture of the beams without any modification to the design.

The mortar from the joint was tested some days after the failure had occurred, but did not receive an adverse report. However, the Author handled some of the mortar from the joint soon after the incident and considered it to be not sufficiently hydrated. Within a few days pieces of it had definitely hardened both in air and in water. He can only conclude that for some reason the dry-packed mortar had not properly set when the water was injected, and that leakage at the joint had sufficiently reduced its strength for failure to occur, there being possibly some irregularity across the joint which resulted in a high concentration of stress.

The incident clearly demonstrates the high degree of control which is necessary in carrying out work of this nature, and it is unlikely that the incident would have occurred had there been, as is generally the case with normal reinforced concrete, a considerable lapse of time before the maximum loading was applied.

150-foot-clear-span Freyssinet Beams

The design of the prestressing cables was such that it was expedient

to erect all the secondary beams before the test, which had the advantage of reducing the actual weight to be lifted into position and afterwards removed by about 100 tons.

The total additional weight which then had to be placed on the main beam to simulate full-loading conditions was 288 tons which, as can be seen in *Fig. 27*, was a considerable task of loading.

The beam was constructed with an initial camber of 5 inches, which was increased to $6\frac{1}{8}$ inches after thirty-three cables had been stressed. The camber was reduced to 6 inches after the total of forty-one cables had been stressed and all the secondary beams had been placed into position.

The deflexion caused by 288 tons of loading was 1·14 inch immediately loading had been completed and 1·25 inch 48 hours later. After unloading there was a residual deflexion of 0·2 inch. The calculated value of E immediately after loading was $5{\cdot}5 \times 10^6$ lb. per square inch.

Fully Bonded 8-inch-by-4-inch Purlins

These purlins were tested with jack loads at third points over a span of 9 feet against a stiff unit.

Jack loads each of 1·5 ton, giving moments of twice the working moment, caused a central deflexion of 0·135 inch.

First cracks appeared at 1·9 ton with a central deflexion of 0·295 inch

The value of E represented by the test load of twice the working load is $6{\cdot}5 \times 10^6$ lb. per square inch.

Fully Bonded 30-inch-by-12-inch Rectangular Beams (for composite construction)

It was not considered necessary to carry out tests on the completed composite beams and tests were made on the prestressed portions only.

These were tested in opposition, as shown in *Fig. 28*, over an effective span of 39 feet with jacks at third points. Loads of 15 tons on each jack, representing 1·5 times the load necessary to produce zero stress in the soffit, produced deflexions of 0·68 inch with a permanent set of 0·01 inch.

The calculated tensile stress in the concrete was 920 lb. per square inch.

The value of E represented by the deflexion is $7{\cdot}5 \times 10^6$ lb. per square inch.

Fully Bonded 45-inch-by-12-inch I-section Beams

Pairs of beams were tested in opposition on a span of 39 feet with jacks at third points. Loads of 72,000 lb. on each jack, which were equivalent to 1·5 times the design loading, produced a deflexion of 0·71 inch and a residual deflexion, when the loads were removed, of 0·03 inch.

The calculated tensile stress in the concrete was 900 lb. per square inch with no signs of cracking.

The value of E represented by the deflexion is $4{\cdot}75 \times 10^6$ lb. per square inch.

lly Bonded 27-inch-by-12-inch I-section Beams

Pairs of beams were tested in opposition on a span of 49 feet with jacks third points.

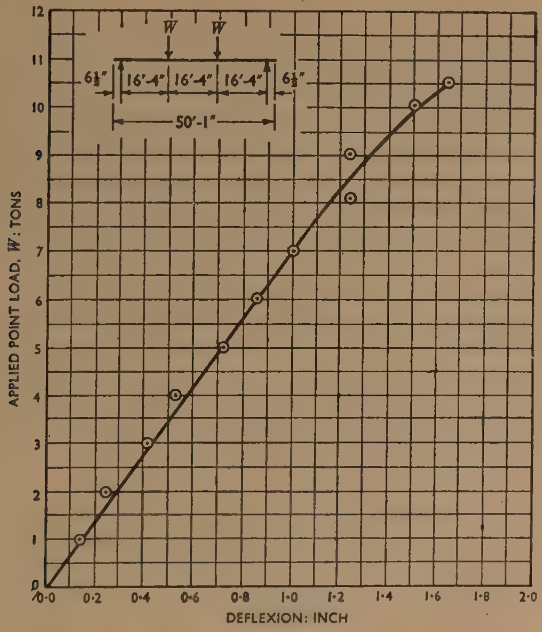
Loads of 10·5 tons on each jack, which gave a bending moment equivat to 1·5 times the design bending moment, produced a deflexion of 1·65 ch and a negligible residual deflexion. The deflexion at 7 tons was 1·0 ch.

The calculated tensile stress in the concrete was 1,130 lb. per square ch and there were no signs of cracking.

The value of E represented by the deflexion at 10·5 tons is $5{\cdot}8 \times 10^6$ per square inch and at 7 tons, $6{\cdot}3 \times 10^6$ lb. per square inch for this am.

A curve which is typical of the various tests, showing loading plotted ainst deflexion, is given in *Fig. 29.*

Fig. 29



TEST-LOADING CURVE FOR A 27-INCH-BY-12-INCH PRESTRESSED BEAM

CONCLUSION AND ACKNOWLEDGEMENTS

The approximate value of the work described in this Paper is £900,000, ich represents about one-third of the total work being carried out on site by the main contractor.

The Author hopes that the enlightened approach of British European Airways in using prestressed concrete for their new base will reassure those who still have doubts on the matter that prestressed concrete may be accepted without misgiving as a sound and well tried method of construction.

He wishes to thank British European Airways for permission to present the information given in this Paper, and their help in its preparation.

The Consulting Engineers acting for British European Airways were Messrs Scott and Wilson; Mr Keith Murray of Messrs Ramsey, Murray & White was the Architect associated with them in connexion with the contract. Mr Philip Evans was the Quantity Surveyor appointed by B.E.A.

The design was carried out by the main contractors, Holland & Hannen and Cubitts, Ltd, in collaboration with Concrete Developments Co., Ltd and The Pre-stressed Concrete Co., Ltd. Mr A. E. Beer was retained by the contractors as Consulting Structural Engineer, in connexion with the scheme.

The subcontractors for the major sections of the work were Concrete Development Co., Ltd (precast prestressed concrete beams), P.S.C. Equipment Ltd (Freyssinet anchorages and jacks), Girlingstone (precast units for hangar roof beams), Lindsay's Paddington Ironworks (crane rails and temporary floor framing), Esavian Ltd (hangar doors), John Williams (Cardiff) Ltd (metal windows), and Aygee Ltd (patent glazing).

Mr L. A. Macer, A.M.I.C.E., was the contractor's supervising engineer resident on the site. Mr A. W. C. Villiers, B.A., B.A.I., M.I.C.E., was the Resident Engineer.

The Author also wishes to thank all those who assisted in the collection of information for and the preparation of this Paper.

The Paper is accompanied by twenty photographs and six sheets of drawings, from which the half-tone page plates, folding Plates 1 and 2, and the Figures in the text have been prepared.

Discussion

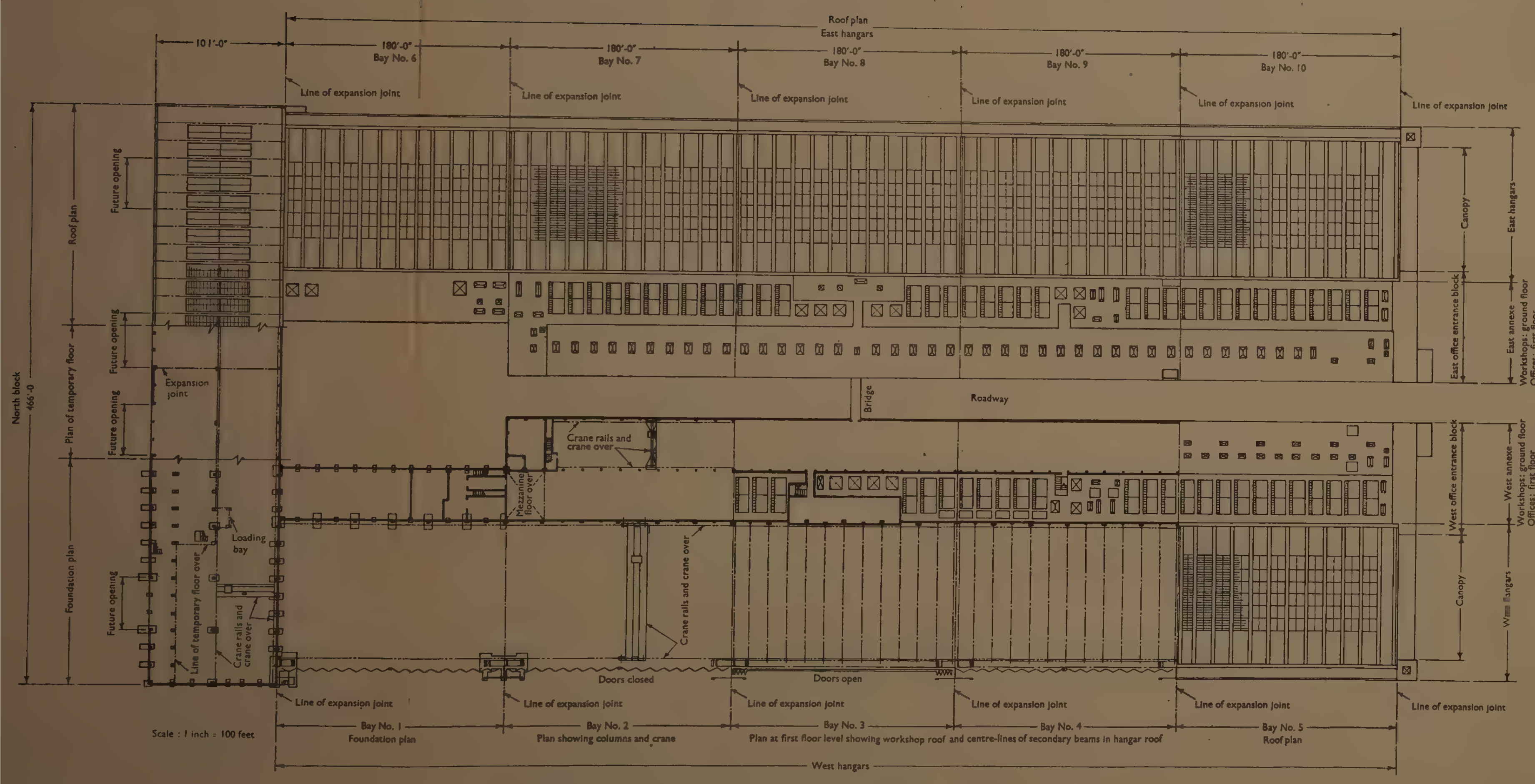
The Author introduced his Paper with the aid of a series of lantern slides.

The Chairman, in proposing a vote of thanks to the Author, remarked that it was just about half a century ago that man learned to fly, and now the aeroplane commanded all the best attention and the best housing which could be given to it. It would probably astonish the Wrights if they could see, after only 50 years, so many civil engineers, contractors,

THE DESIGN AND CONSTRUCTION OF THE B.E.A. HANGARS AT LONDON AIRPORT

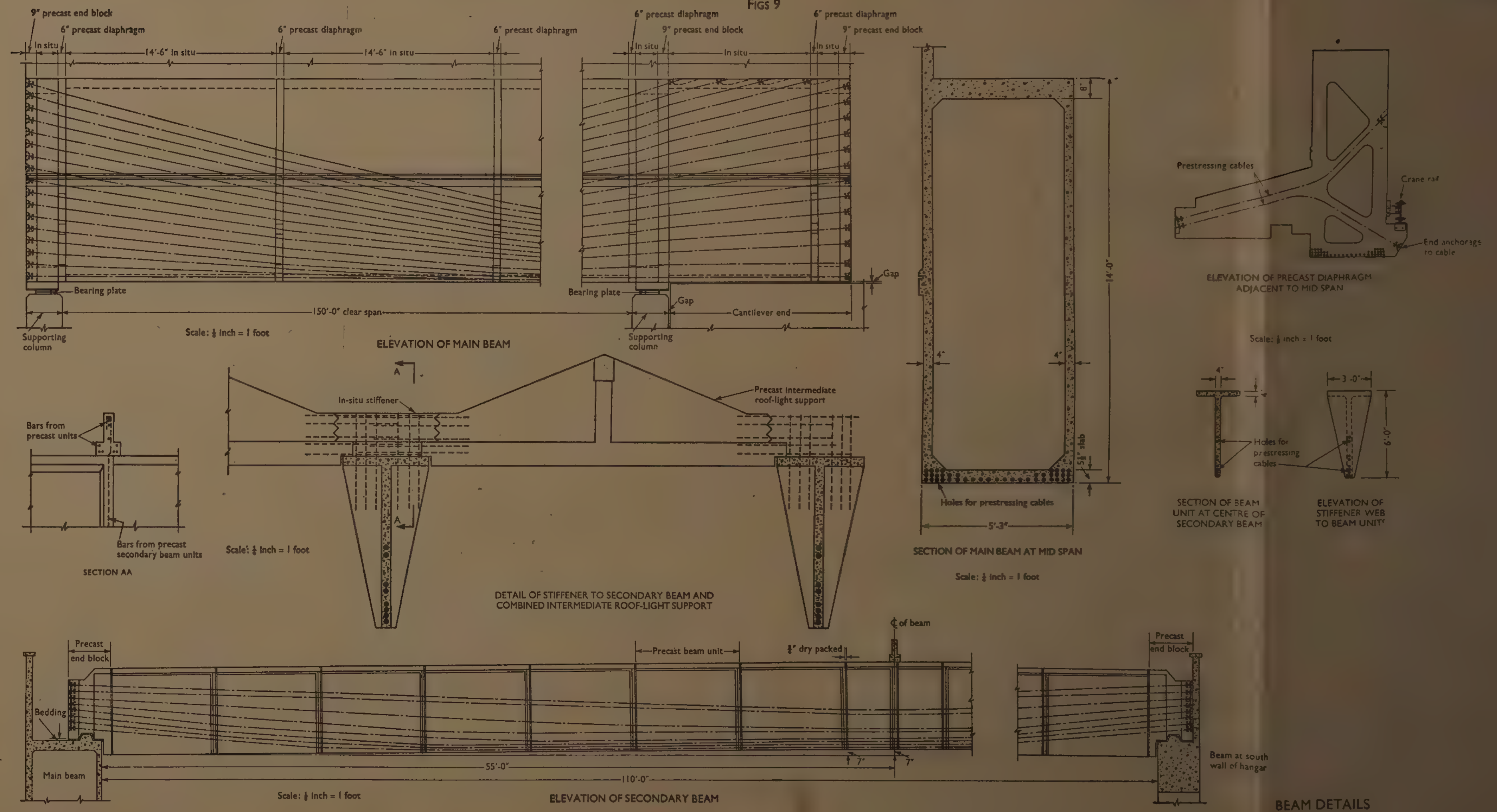
PLATE I
B.E.A. HANGARS
LONDON AIRPORT

FIG. 1



PLAN OF HANGARS, NORTH BLOCK, AND ANCILLARY BUILDINGS

FIGS 9

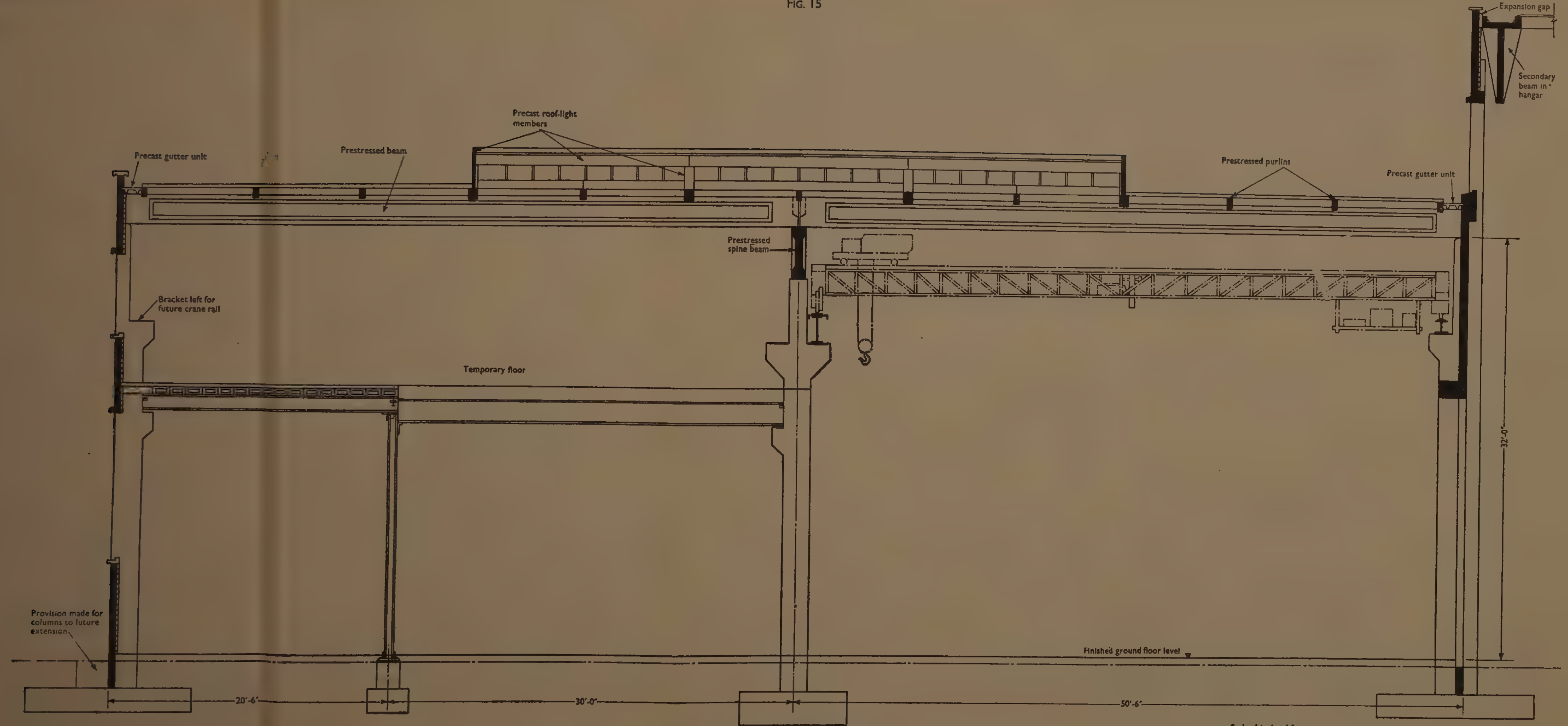


BEAM DETAILS

D. H. NEW

THE DESIGN AND CONSTRUCTION OF THE B.E.A. HANGARS AT LONDON AIRPORT

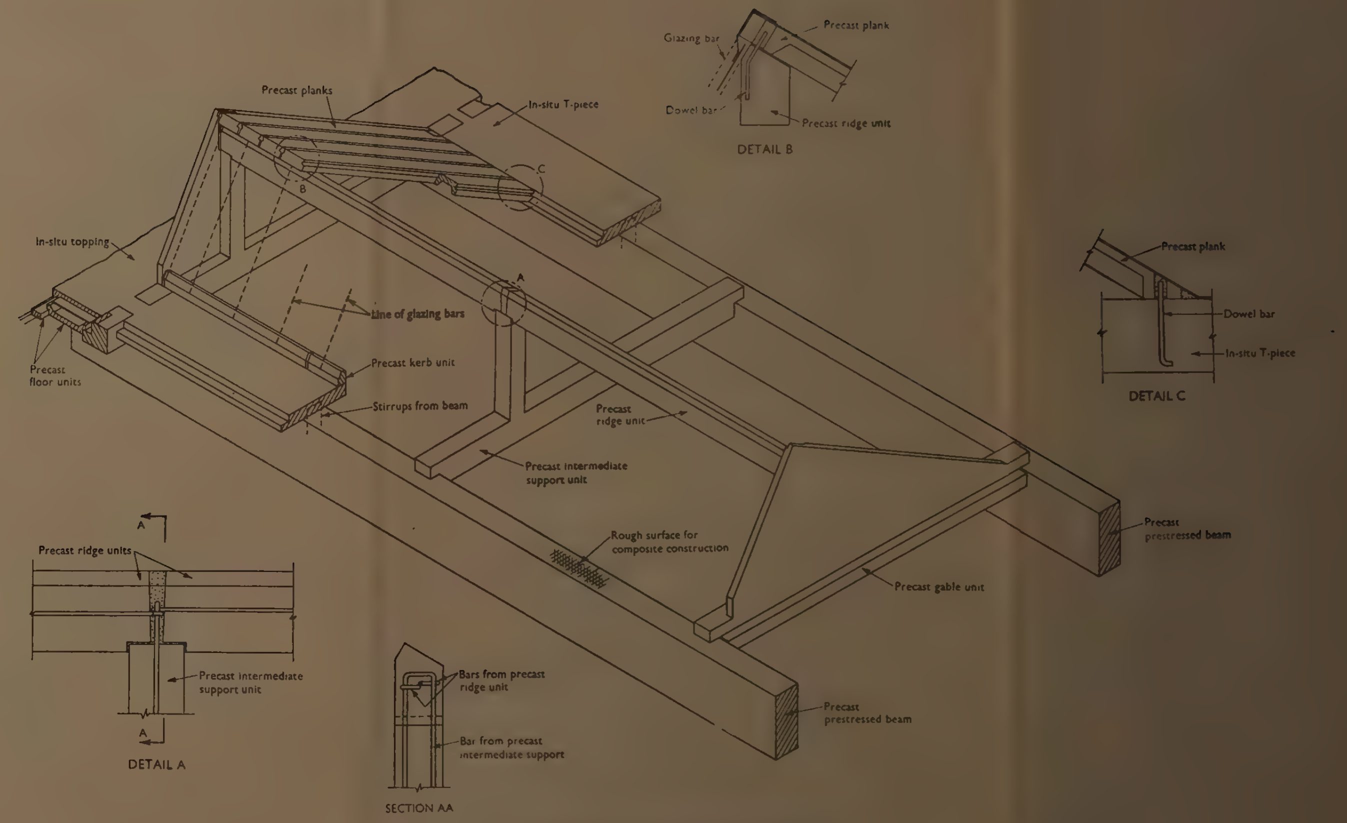
Fig. 15



Scale: ⅛ inch = 1 foot

CROSS-SECTION OF NORTH BLOCK

Figs 21



SKETCH OF NORTH-LIGHT ROOF TO ANNEXE

D. H. NEW

William Clowes & Sons, Limited: London

architects, and designers catering for their invention by the erection of those large and beautiful assembly halls, sheds, and hangars.

Mr A. E. Beer emphasized that it was unusual for a contract of the type in question to be let in the form of a design-and-construction contract, but the result had been very successful. The work involved the marrying of precast concrete, normal in-situ concrete, and prestressed concrete to a degree which was probably more extensive than anything else done in Great Britain before. That had resulted in a considerable economy in steel and Mr Beer quoted some figures in confirmation. For one bay of the main hangar building, 180 feet by 110 feet, the total area enclosed was 22,800 square feet. The weight of mild steel per square foot was 3·47 lb. The weight of high-tensile wire per square foot was 1·26 lb. The total weight of steel per square foot was therefore 4·73 lb., which included walls, columns, and roof construction. For the same bay, the enclosed volume was 1,200,000 cubic feet and the total weight of steel per cubic foot was 0·0916 lb. Both of those totals represented approximately one-quarter of what would be used on a structural-steel-framed building of the same dimensions.

For the North Block, the corresponding figures were as follows :—

Total area :	47,000 square feet
Total enclosed volume :	1,890,000 cubic feet
Weight of mild steel per square foot :	3·73 lb.
,, H.T. ,, ,,	0·56 lb.
Total weight of steel per square foot :	4·29 lb.
,, ,, ,, ,, cubic foot :	0·11 lb.

A further interesting figure was the steel/concrete ratio. For the hangar and the prestressed members the ratio was 1 ton of high-tensile steel to 26 cubic yards of concrete, and for the prestressed members it was 1 ton of mild steel to 31 cubic yards of concrete. In other words, the content of high-tensile steel and the content of mild steel were approximately the same. For the normal reinforced-concrete members in the hangar, the ratio was 1 ton to 28 cubic yards of concrete. In the North Block, for the prestressed members, it was 1 ton of high-tensile steel to 21 cubic yards of concrete and 1 ton of mild steel to 38 cubic yards of concrete. In the case of the normal reinforced-concrete members in the North Block, the figure was 1 ton of mild steel to 21 cubic yards of concrete.

Those figures showed an excellent relationship compared with reinforced concrete, where the ratio would normally be between 1 to 10 and 1 to 15.

Mr A. J. Harris emphasized that the originally proposed design of the structure had envisaged a crane rail down the middle, which would have imposed a load of 22 tons in the middle of the secondary beams and transformed what was a roof into something not very different from a highway bridge. That had, therefore, been the starting point for the design of the shape of those secondary beams. Mr Harris did not mean to infer that

otherwise the final outcome would necessarily have been different ; nevertheless, the original design would have resulted in a very large point load on the centre of those beams, which would need, it was thought, a solid-web beam to carry the high shear stresses and fatigue effects which would be produced by a crane.

Another factor, which had a considerable bearing on the shape of the job as a whole, had been the insistence that each of the bays should be completed separately, and should be rendered entirely separate structurally by an expansion joint dividing them completely one from another, with the original intention of being able to hand over each complete bay as soon as completed ; it had, therefore, not been possible to arrange continuity between the separate bays. The first thought had been that it might be built as a complete monolithic whole, but that had not been possible, and therefore the nature of the roof had to be that of a sort of flat plate, resting on two struts in front and a wall down the back. The obvious way of doing that was to have a heavy beam over the front with a series of secondary beams spanning from the wall to the heavy beam. That beam had to carry horizontal wind loading as well as vertical loading ; there was a canopy in the front, and the roof at the back was not in the same plane vertically or horizontally, and in consequence off-centre loads could be applied and considerable torsion could result. That was the reason for the hollow box section, because an I-section, however stiffened, would not have been sufficiently substantial.

That raised one of the points of practice to which considerable thought had been given, namely, where the cables should go. The hangars at Melsbroek were an eminent precedent for putting them in the void in the middle. That had been decided against, however, because if the prestress force passed down the middle of the beam, it acted externally on the webs, and not only did the forces arising from external loads tend to buckle the webs, but the prestress force as well, which force, in the present case, was of the order of 1,000 tons. Since the vast majority of the concrete was actually lying in the webs, it had been thought wiser to avoid that tendency to buckling by burying the cables in the webs themselves, and the thickness of the webs could thereby be reduced to about 4 inches. It was a curious fact that in both the main and the secondary beams, 4 inches, which was about the minimum practical thickness of concrete which could be cast with a cable going through it, had been ample to take care of all the shear effects. Even if a very much stronger concrete, capable of carrying very much higher stresses, had been considered, Mr. Harris did not think that, on beams of the nature in question, it would have been possible to reduce the thicknesses below those in fact adopted. It had therefore been decided that the main beam should be a hollow box with the cables passing through the webs.

The secondary beams had not presented so great a problem. Buckling during lifting was something which had to be watched, and that had fixed

the breadth of the top flange. Moreover, by virtue of the incidence of horizontal loads—the wind drag actually acting on the surface had had to be investigated—there was a certain amount of torsion and transverse bending. All those factors had had to be considered, and the section had been chosen for the primary effects, and a check was made on the secondary effects. He emphasized that the web thickness of 4 inches was small, particularly when it was desired to get a good deal of good concrete into it, as had had to be done in the case in question because the stresses were high; moreover, in the webs in the main beams a cable and a certain amount of secondary mild steel were passing through that 4 inches of concrete, and cover had to be ensured. Great care had therefore had to be exercised in the casting of those webs, and also in casting satisfactorily the precast elements in the secondary units; the possibility of doing that had been a question for consideration between the designer and the contractors in the early stages of design. The contractors had said that they could do it, and the care which they had exercised had been exemplary.

Mr F. H. Fielder said that he had been associated with the making of the units for the secondary beams. There were 130 beams, 110 feet long and of 26 tons weight, and they were made up of 2,340 T-section units 6 feet deep and 3 feet wide, with an average weight of 29 cwt per unit. Only eleven moulds had been employed for those 2,340 units. It had been known from the beginning of the contract that the work would be placed in good time, and the number of beams which it was thought could be produced per week was specified; on that basis it had been calculated that eleven moulds would suffice, the average use of each mould being 213 casts. In the case of the standard T-section unit an average of 260 casts had been obtained from each mould. He did not think that, for any reinforced-concrete structure of normal design, one could envisage the use of formwork for half a beam, which was in fact what had been used for the hangars in question, nor could he imagine the number of forms which would be required to produce the necessary number of beams with the speed which was required. He thought, therefore, that the contract had been unique and interesting by virtue of the economy obtained by the use of the form of construction in question.

The work had not been easy, because, as had been stated, the web and flanges of the units were only 4 inches thick. Within that thickness there were the eight $1\frac{1}{4}$-inch-diameter tubes, longitudinal $\frac{1}{4}$-inch bars, and transverse $\frac{3}{8}$-inch bars; furthermore, concrete spacers had to be used to ensure the correct cover, a mass of pins to form holes, wooden blocks, etc., had all added to the magnitude of the problem of filling the moulds.

In order to conform with the basic idea of doing the work within the terms of the economy which it was thought could be achieved, a 24-hour cycle had had to be obtained for the striking of the moulds and the handling of the units; and that had necessitated some consideration on the question as to how the moulds were to be made. Instead of running the tubes so

that they would pass through either end of the mould, which would locate the tubes accurately (since they had to be within a tolerance of $\pm \frac{1}{32}$ inch) they were turned completely through 90 degrees, because it had been felt that to make them in what might appear to be the easy way would complicate the filling by virtue of all that had to go into the 4-inch web, and there would have been airlocks underneath the tubes. They had therefore cast them with the tubes sticking uppermost. That had the advantage that they could fill the moulds comparatively easily, and when the problem of stacking came to be considered they had a 3-point support from the cross-section of the tee, the stiffening flange being the top of the mould, and there was no need to turn the casting in its green state.

To locate the tubes there was a form of bolster running across the top of the mould, and jigs at the top and bottom ensured them being placed very accurately, but that left very little room for filling, because they had only a 4-inch web and the stiffener was only 2½ inches thick, with the bolster immediately above that, so that they had a space of about 4 inches and had to achieve the strength of concrete required, which was 6,000 lb. at 14 days, although the majority of tested cubes had strengths of between 7,000 and 8,000 lb. per square inch.

Workability had been a paramount consideration. The first few units had been experimental, but eventually a concrete had been obtained with both the workability and strength required; the mix was approximately 1 : 1 : 2. Whenever the temperature had dropped to about 45° F. or less the concrete had been pre-heated in order to maintain the 24-hour cycle. The ballast and sand had been heated to about 100° F., and the water probably somewhat hotter, the mix of concrete delivered to the mould being at a temperature of 70° F. At 24 hours regularly the moulds had been struck and the 29-cwt units lifted from their position and transported to the stacking site.

The kind of concrete employed could not be dumped; it would not "pour" from the scoop of the hopper, and the whole of the concrete for those beams had to be shovelled. The pre-heated concrete gave some trouble, because it tended to let the mould oil run down the surface and collect in the bottom edge, that was, the very important 4-inch edge which was abutted to the neighbouring unit. The engineers supervising the work seemed to think that the oil, which left a dark mark in the bottom of the unit, tended to weaken the concrete. As an alternative, paraffin wax had been used in the proportion of ½ lb. of wax to 1 gallon of white spirit; that was brushed on the moulds, and the spirit evaporated leaving a thin paraffin-wax skin. That had solved the problem and had proved to be a better mould oil than any of the proprietary brands previously used.

Vibration had been achieved with two A.V.5 Allum vibrators, one mounted at the bottom and one at the side, and a small A.V.3 on the flange which, of course, was vertical on the mould. The life of the ½-inch-thick steel plates, which has been used to mount the vibrators on the

moulds, had been 2 days, after which they had split; $\frac{3}{4}$-inch-thick plates had lasted about a week. Mounting the vibrators on frames so that the throw was vertical instead of horizontal through the mould had eliminated any further trouble.

Mr L. A. Macer said that at the time of tendering for the original contract, a basic programme had been prepared in the form of a skeleton chart showing: (1) requirements of the clients for taking into use the various sections of the building; and (2) the sequence of repetitive operations to which the work lent itself.

When the work commenced, and throughout the contract to date, period programmes based on those original basic charts had been prepared and used for limited periods of about 6 months at a time. The function of the planning section had been to fit the subsequent work, which had been added from time to time, into the basic programme.

The work of the specialist services had presented the major problem. In the course of the preparation of the very first of the period charts it had become obvious that the speed of the job would be dictated by the requirements of the clients and by the specialist services, rather than the normal sequence of the structural work. In fact, the latter had in some cases to be altered to suit the requirements of those services. A typical example had been the ducts for the heating mains which served the job from a central boiler-house plant and which had had to be constructed in the reverse direction to the sequence of the main structure. In consequence, being an integral part of the structure, they had been re-designed and prepared accordingly. A further point in that connexion was that the ground work inside the hangars had to be carried on while the superstructure was being built overhead, as against the normal practice of completing the ground work before starting on the superstructure.

The period charts, as prepared, had been modified on a number of occasions to take into account additional items of work as the requirements of the clients became known. The extent of those modifications had been indicated by the Author in the concluding part of the Paper, where it was shown that the overall value of the contract was now about three times that for the original basic structure. The main function of planning on the contract had therefore been to foresee the effects of all those modifications and to minimize the resultant drag on the main structural work.

A point which might be of interest to those who had concerned themselves considerably with the ability of contractors to produce high-grade concrete at the site, was that during the course of the contract a series of test cubes had been regularly taken on both the normal reinforced concrete and the prestressed concrete, and the following figures indicated briefly what had been achieved. For the normal reinforced concrete, approximately 150 cubes had been tested at 28 days; the average strength of those cubes was of the order of 5,000 lb. per square inch, and only 3 cubes

had been below the specification strength of 3,300 lb. For the prestressed work, 56 cubes had been tested at 14 days, and the average strength achieved there had been 7,050 lb. per square inch, as against the specification strength of 6,000 lb. To date, a total of more than 600 cubes had been cast on the site and had been crushed at various ages between 3 and 28 days for the purpose of establishing strengths to enable prestressing to go on.

He had mentioned earlier that a number of items of work had been added to the contract from time to time. One of the most interesting was a basement structure for the incorporation of a test-bed. The design had been prepared by the consulting engineers and incorporated a certain amount of prestressed work. The problem presented to the contractor was that the work had to be carried on inside the main hangar construction and in conjunction with it, at a very late stage of the job. The question of excavation and pumping had had to be considered; water was normally found on the site at about 8 feet below ground level, and that basement went to a level of 18 feet below ground. The problem had been solved by a battered excavation to water level, followed by driving light steel sheet-piles from there into the clay subsoil to formation level, and pumping continuously until the structure was brought up to the level of the water. A number of alternative methods had been considered including dewatering, and certain other sites in the area had been visited, but the consulting engineers had decided, in conjunction with the contractors, that the method adopted would be the most economic, and it had proved very effective.

Mr E. O. Measor emphasized that although the structure described by the Author was probably the most interesting part of the scheme to civil engineers, it should not be imagined that it was just an empty unit into which aircraft were towed. The structural work which the Author's firm had designed and constructed represented about 40 per cent of what was really an elaborate factory, with an interesting scheme of mechanical services.

In the last paragraph on p. 16 the Author had stated that tenders had been obtained to contractors' own designs on the basis of the outline drawings prepared by the Ministry of Civil Aviation. That was the kind of tendering method which Professor A. L. L. Baker had advocated in his letter to *Chartered Civil Engineer* of September, 1952. Mr Measor found himself in considerable disagreement with some of Professor Baker's suggestions, but he did believe that that method of tendering had, in the present case, produced an interesting design. In contradiction to Professor Baker's views, however, he believed that it had been only a happy chance, and it certainly did not prove that interesting designs or new developments were regularly produced either by Government subsidies of millions of pounds or by methods of tendering. The result depended on whether engineers of original mind happened to be interested in a given

problem at a given time, and also on the desire of the engineering profession in Great Britain to try out new methods and on the willingness of those who paid for the buildings to have new methods tried out on them.

The Author had stated that since the construction of the hangars had been a contractor's scheme, it had been possible to increase efficiency and economy by investigating erection problems more closely at the design stage. It was, of course, true that a contractor would always prefer his own ideas to somebody else's, and equally true, probably, that he would approach the pricing of his own ideas in a more sanguine frame of mind. The engineer producing a design to be priced by a number of contractors had to reflect on the fable of the miller, son, and ass, from which he would learn that if he tried to please everyone he would end by pleasing no one. To assume that there would always be a contractor who could produce a more efficient and economical scheme than any engineer engaged purely on design, would be to overrate the wisdom of contractors and be scarcely flattering to engineers who spent their lives in designing structures.

Mr Measor agreed with the Author that something better than a slump test was absolutely necessary for high-strength concrete work. Mr Fielder's description (see p. 46) would indicate the kind of concrete to which the slump test was not at all applicable.

From p. 23 it would be noted that for the rear wall of the hangar the contractors had made an experiment with a mobile and rather formidable-looking arrangement of shuttering. It would be interesting to know whether the Author felt that that arrangement had been successful from the points of view of progress and economy.

On p. 27, the Author had expressed the feeling that the slim lines of the 4-inch flanges of the T-beam were a contribution to modern architecture, and had called attention with regret to the strip-lighting fittings which had been attached to them. Mr Measor felt that the Author's criticism was also rather slender! Appreciation of the thinness of those flanges was in any case much reduced by the limited degree of freedom of the human neck. *Fig. 8* showed the general impression one gained of the interior of the hangars. Mr Harris had pointed out that the original scheme had called for two cranes which would have led to heavy point loads on the secondary beams, and the secondary beams as originally designed had not had a thin edge at all but a bottom flange, so that it might be said that the thin edge arose merely as an outcome of the change in the scheme, which Mr Measor's firm had introduced, thus affecting a considerable economy in the design of the roof.

Mr Measor did not agree with the Author's opinion regarding the fitting of lights to the 4-inch flanges of the T-beams, and he did not think that that thickness was at all good on engineering grounds. He had criticized that feature at a very early stage, and he felt even more convinced now that the bottoms of those flanges should have been thicker. Where there was a heavy concentration of holes for prestressing cables

along the edge of a beam and, as in the case in question, there might be perhaps five $1\frac{1}{2}$-inch-diameter holes very close together, there was only a wall of concrete $1\frac{1}{4}$ inch thick on either side, and he thought that a thickening of the web to 6 inches, for a depth of 12 inches, would have been a very great improvement. *Fig. 26* illustrated the difficulties which arose from a concentration of holes near the edge of a member of the kind in question.

The cold-cathode lighting system was one of the largest, if not the largest, of that type executed in Great Britain, and he thought that every-one who had seen it agreed that it was extremely pleasing. Further, suspension of lighting fittings between the beams would have masked some of the light from the windows, and would not have appeared so neat.

In the last paragraph on p. 27, reference was made to the linking together of the prestressed beams by mild-steel reinforcing bars between the columns and the beams, forming a space which had been eventually filled with in-situ concrete. The joining together of the members in a neat fashion was very difficult in prestressed design, but the Author's design had produced a neat and effective result. The difficulty was to avoid too great a fixity at the ends of the members and also the trans-mission of too great horizontal forces. Mr Measor thought that the design adopted did get over that difficulty.

With reference to the foundations for the precast columns, the descrip-tion of what had been done was not very clear. He would like to draw attention to the question, because he thought that it was of some interest. The bottom of each column had been slightly chamfered, and it was on those chamfered faces that the load of the column was carried. The recess in the foundation block was concreted with a ring of reinforcement to take the bursting effect. The column had a small flat projection on the bottom, on which it could be rested while it was being concreted. The object of that method was to avoid the difficulty of concreting under a horizontal surface.

Although certain schools of thought viewed the introduction of any mild-steel reinforcement as something to be deprecated in prestressed design, Mr Measor considered that a light mesh of mild-steel reinforce-ment was absolutely necessary to impart toughness to the concrete. Would the Author give his opinion on that subject?

Professor A. L. L. Baker, who was invited by the Chairman to reply to some of Mr Measor's remarks, thanked Mr Measor for, perhaps un-intentionally, pointing out that there was a certain amount of sense in the letter which he had written to *Chartered Civil Engineer*. It was a happy event that there should be such a magnificent piece of pioneer con-struction so near London, where it was easy to go to see it, and of which it could be said "Here is an example of what happens when you have a competition."

He felt that it would help the design engineers in Great Britain tremendously if from time to time a competition of that kind were to be held, particularly with structures which were liable to be repeated, and suggested that a power station be used as an example next time. Professor Baker thought that such a proposal ought to have the support of consulting engineers, because in the long run they would find that the standard of design would attain a lead over that in other countries, and that it would help Great Britain in obtaining work abroad and in maintaining contacts abroad—when consulting engineers obtained work abroad, business always followed.

He thought it was most important that a competition of that kind should be repeated ; he was not in the least repentant about his letter, and felt that he had done the consulting engineers a good turn. People in India, in the colonies, and elsewhere would hear about the hangar which had been built at Heathrow and would give the credit to British consulting engineers. Probably some of the work had been done in a Paris office, but much had also been done in Great Britain, and he was sure that it would lead the way to obtaining further work for Britain abroad ; therefore, adding to what he had said in his letter, he thought that, as a result of such competitions, Britain would build up a great name for civil engineering design in the world again, which it had been losing in favour of France, Belgium, Germany, and some of the Scandinavian countries, where prestressed concrete and shell construction had originated.

It would be interesting if the Author would indicate the kind of cube-strength variation which had been obtained with both kinds of concrete. Professor Baker was of the opinion that it would be useful for engineers in the future to know what kind of variations in strength might be expected under conditions of control such as had been employed at Heathrow. Would the Author also say a little more about the grouting-up of the cables ? The procedure adopted had been described, but it was a matter on which more information would be welcome. Perhaps he could add something which would show convincingly that the method adopted was foolproof and made it certain that the cable was thoroughly grouted, and that there would be full bond between the cable and the concrete.

Another point of interest was the relative cost of the 2,500-lb.per-square-inch concrete and the 1,100-lb.-per-square-inch concrete. It would be interesting to know whether it cost a great deal more to produce concrete having a crushing strength of 2,500 lb. per square inch. On many jobs it would be of very great advantage to use such concrete, if it did not cost a great deal more, and Professor Baker suspected that it might not.

With regard to the design, could a little more information be given about the possibilities of providing continuity in the main beams ? In principle it seemed that a long beam over several supports should, if possible, be continuous in order to reduce the bending moment, and it

seemed to Professor Baker that perhaps in a future design it might be possible to provide continuity with some form of cap cable over the supports, putting the right amount of prestress into the cable so that the mid-span moment was almost equal to the support moments.

Dr K. Hajnal-Kónyi referred to the point raised by Professor Baker about the reliability of the grouting, and suggested that an opportunity had been missed to prove the efficiency of the grouting. He mentioned the test of the 110-foot-clear-span beams and said that he had been very interested to compare the various units tested and had been rather surprised at the test load applied. On p. 37 it was stated that the total bending moment due to the remainder of the dead load and to the live load was 10,270,000 lb.-inches. The test load placed on each beam had been 24 tons, in the form of 3-ton cast-iron blocks. With good approximation that could be considered as a uniformly distributed load, and if so, the bending moment had been only 8,860,000 lb.-inches, so that the test load had been only 86 per cent of the full design load. On p. 38 the Author had given the stresses on which the design had been based. The compression in the bottom due to the residual prestress (presumably after accounting for all losses) with a cable load of 54,000 lb. was 4,200 lb. per square inch, which, under the dead weight, was reduced to 2,325 lb. per square inch, but that was assuming the full loss of prestress after relaxation and creep, and presumably at the time the test took place the compression in the bottom was much more than the calculated value. The compression in the bottom under the full design load was given as 85 (475) lb. per square inch. The figure in brackets applied if the grouting was fully efficient. It would have been an excellent opportunity to load that beam to at least such an extent that 475 lb. per square inch would have been exhausted and zero stress reached, but in fact the test load did not even reach the design load. It was a great pity that the load had not been taken further.

On p. 41 reference was made to other tests on fully bonded beams. Each of them was loaded to 1·5 times the load necessary to produce zero stress, and there were no signs of cracking at calculated tensile stress in the concrete of 900 to 1,130 lb. per square inch. With a structure such as the 110-foot-span beam, which was composed of precast units, it could not be expected that any substantial tensile stress would be taken up because the joints would open up, but it would be reasonable to assume the grout to be fully efficient.

That was a question which had interested Dr Hajnal-Kónyi ever since he had studied the Freyssinet system. He had asked the question repeatedly and had been assured that the bond was fully efficient, but so far he had never seen any experimental evidence that it was in fact so *in a beam made on the site.* It was too late now to do it, but it would have been better to go further with the loading.

Mr E. F. Humphries drew attention to a difference of method employed in the work described in the Paper in regard to the composite

construction from that described by Mr Samuely,[1] who had achieved the necessary key between the prestressed precast unit and the in-situ concrete (to take the horizontal shear) by means of castellations cast on the unit. In the work described by Mr New that key had been achieved (in Mr Humphries' opinion, much more effectively and easily) by having the top of the units roughened as pointed out in the Paper, that roughening being achieved simply by leaving the concrete as it was when the vibration finished, and by going over it with a hand tool and tamping vertical grooves across the unit into the top surface. When the in-situ concrete was placed, the keying together was satisfactory and gave the necessary strength to take the shear, together with the rods which had been left projecting from the top of the unit.

Mr Humphries mentioned an example of creep which had been forcibly brought to his notice in the case of the work described, and which he thought might be of interest. Some of the 50-foot-long I-section units, when first made, had been stacked on timber bearers at the works. They had been handled by means of lifting-eyes cast in the top of the unit in the usual way at about the quarter points, which were burned off after the units had been put into position on the job. Owing to a change in the delivery schedule, a few of those units had been left on the site of the works for several weeks, and the bearers, by an oversight, had been placed underneath the lifting eyes at the quarter points. Those units were, therefore, supported at the quarter points, and the cantilever effect of each end, together with the eccentricity of the prestress, was enough over a period of several weeks, to cause hogging, which, when the units were released off the long-line process was roughly $\frac{3}{4}$ inch, to increase to more than 2 inches. He did not know whether anyone had noticed that in some of the beams there was a slightly increased curvature of the soffit, but it gave a very clear picture of what did happen with concrete under load and how in a relatively short time a change in shape could occur. Although those units had been very carefully examined for any possible tensile cracks which might have occurred in the top surface, and were also subsequently tested, so far as he was aware they were perfectly sound and they had been accepted and built in the work.

He would like to pursue the point raised by Professor Baker with regard to continuity, and to ask the Author whether in fact consideration had been given in the design of the structure to trying to tie the 40-foot-span beams and the 50-foot-transverse beams together to give a continuous structure.

He would also like to know whether it was possible to have any indication of the price per square foot or per square yard of the building for the secondary 110-foot-span beams and the roofing carried, ignoring the main

[1] F. J. Samuely, "Some Recent Experience in Composite Pre-cast and In-Situ Concrete Construction, with Particular Reference to Pre-stressing." Proc. Instn Civ. Engrs, Part III, vol. 1, p. 222 (Aug. 1952).

150-foot-span beams, because it would be very useful to have that information to apply to similar large structures. The 150-foot-span beams were a special feature of the hangar described, but the remainder of the type of construction adopted might equally well be applied to a power station or something similar.

Mr E. H. Bateman, referring briefly to the subject of design competitions, said that his first experience in a consulting engineer's office more than 25 years ago had been concerned with designs prepared for a competition for the Howrah bridge, held about the year 1909. The prize-winning design had been one which not even the most ambitious engineer would have ventured to put into practice, and it had very properly been turned down in favour of the cantilever which stood today. That design had included a double-leaf rolling-lift bridge on pontoons, which were to be anchored by an ingenious device in that fast-flowing tidal river, and the leaves of the bridge were to close and the jaws to lock in all conditions of wind and water. In his opinion, the consulting engineers at that time had adopted the right course by ignoring the result of the design competition, and he hoped that there would be no hesitation in future in taking a similar decision if it were felt that a winning design was unsafe, or that there were other good reasons to justify its rejection.

The Author, in reply, said he was very pleased that Mr Beer had made a point of the small steel content of the building, because if regard were to be had to the national economy that was an aspect which should be kept well in mind for some years to come.

He was also very glad that Mr Harris had enlarged a little on what might now be called the history of the job in its early stages, and agreed that anything other than a 4-inch web would not have been practicable from a constructional point of view. It would be appreciated that the disappearance of the large crane-loads from the middle of the 110-foot-span roof beams had greatly simplified the design problems.

Mr Fielder had drawn attention to the very considerable economy in formwork which could be obtained by using precast construction, and had given an excellent description of the particular problems involved. The tendency to turn more to precast work had been mentioned in the Paper, and there was an increasing compulsion to adopt it as a matter of economics. No doubt some engineers would bear in mind Mr Fielder's suggestion of a paraffin-wax skin instead of mould oil, which might prove useful at some future date when heated materials were being dealt with.

Mr Macer had emphasized the value of planning, a matter which invariably led to trouble unless given due attention. From the financial aspect, the Author considered it essential that every job should be controlled by a well considered plan, with flexibility to allow for inevitable delays and amendments during the course of the work.

He was very pleased that Mr Measor had mentioned the services, which were in themselves a major work, because a magnificent show had been made

of them. Their magnitude alone prevented their inclusion in the Paper, but they were in themselves worthy of presentation to the Institution and it was to be hoped that that might be possible in the future.

The Author was pleased also that Mr Measor agreed with him on the use of some type of Consistometer instead of the slump test. He felt that, for the type of work which was now being done, the slump test was a primitive instrument and should be dispensed with as soon as possible.

The mobile shutter had in general been very successful, especially on the west hangar. For reasons beyond the control of the contractor it had not been so successful on the east hangar. For an entirely straightforward job it would have been very good indeed, but its full efficiency had been interfered with when the test-bed, the construction of which had not originally been anticipated, had been introduced.

Mr Measor had offered some criticism of the 4-inch web of the tee in the 110-foot-span beams, and the Author felt that he also could work up a very good case as to why 4-inch webs to those tees would be highly unsatisfactory, but the fact remained that those webs had been successfully used. The units had been made, put together, and stressed, and they were all in position (with the 4-inch webs masked by strip lighting!), thus giving practical proof of the case in favour of 4-inch webs.

The Author had not drawn particular attention to the inclined faces at the base columns, because in all the other jobs which he had done in that way—and he had done a number—those faces were not inclined, and neither did he consider it desirable for the general case.

He agreed with Mr Measor that it was advisable to have a measure of mild steel in prestressed concrete units, but was not able to give a general rule as to how much, or how it should be arranged. He knew that it was often suggested that for all kinds of fully bonded units it was possible to dispense entirely with mild steel, but he felt that that would eventually lead to trouble. It was a subject on which very little useful knowledge was available, and it might be prudent to incorporate a little mild steel, as in fact his own firm had done in all their work so far, until somebody was able to prove that it was not necessary.

He did not propose to take part in the argument between Professor Baker and certain consulting engineers over competitions, although it was evident that in the particular case in question the competition had been well worth while and had produced something useful.

With regard to the grouting of the cables, no opportunities had arisen for a study of that point. He was aware that in certain cases which had come to light, though not on the job described in the Paper, cables had been found not to be fully grouted. It was stated in the Paper, which had been prepared some time ago, that a 1 : $1\frac{3}{4}$ cement-sand grout had been used. That had been satisfactory for the 110-foot-span beams, but eventually it had been found unsatisfactory for the longer span beams, and a pure-cement grout with a water/cement ratio of about 0·53 was now used. With

regard to the unit cost of the concrete, there would be a considerable difference there due merely to the cement content. The stronger concrete had been made in a factory and the other on the site, so that they were not strictly comparable.

In referring to continuity, presumably Professor Baker had in mind the main beams. The five hangars were completely isolated from one another and no effort had been made to make them continuous, because it was not desired that they should be so. The Author did not think that it would have been desirable to have a structure 900 feet in length with the main beams continuous.

While due credit must be given to France for the evolution of the basic methods of prestressing, he could assure Professor Baker that the scheme at London Airport was entirely a product of British engineers.

With regard to the testing of the 110-foot-span beams, he agreed with Dr Hajnal-Kónyi that it might have been very useful had the tests been carried much further. In general, that principle applied to almost every big job, and mainly for economic reasons full-scale research opportunities were lost daily. It was, of course, a very simple matter to subject a beam to a 50-per cent overload, when loading was carried out by means of jacks.

The test load on the 110-foot-span beams was not quite evenly distributed, but was so placed that the correct design moment was attained.

Mr Humphries had referred to the composite construction which had been employed to a large extent in the annexes, and he was undoubtedly right about roughening the surface. It was not a good thing to raise castellations; it could not be done satisfactorily, and the Author would recommend roughening the surface and, if that were considered insufficient, making indentations in the top with a hand tool.

Mr Humphries had also mentioned the storage of fully bonded beams, which should normally be supported at the ends only. It was possible, as they had found out in conjunction with the Ministry of Works some years ago, to lift and transport a beam with about 450 or 500 lb. per square inch of tension, but if it were stored for some weeks in that same state, undue deflexion would occur.

There had been no question of attempting continuity for the North Block in either the 50-foot-span or the 42-foot-span beams, and it was his opinion that continuity would have had the effect of increasing cost.

Mr Bateman had referred to the design competition for the Howrah Bridge. It was the Author's view that a design competition was very little use unless those who submitted the designs had to do the construction and take full responsibility for it. A competition on those lines might well produce something useful, but a design on its own, not linked with construction, was unlikely to lead to the most economical job.

The closing date for correspondence on the foregoing Paper has now passed and no contributions other than those already received at the Institution can be accepted.—Sec. I.C.E.

WORKS CONSTRUCTION DIVISION MEETING

9 December, 1952

Mr David M. Watson, Member, Chairman of the Division, in the Chair

The following Paper was presented for discussion and, on the motion of the Chairman, the thanks of the Division were accorded to the Author.

Works Construction Paper No. 22

"Economic Use of Heavy Earth-Moving Equipments and Field Maintenance thereof"

by

Bernard Joseph Meighan, A.M.I.Mech.E.

SYNOPSIS

Very early in history, about a hundred thousand Egyptian slaves struggled for 30 years to place three million cubic yards of material into the Great Pyramid of Cheops, on the bank of the Nile. Today, with modern mechanical equipment, such a task would be a simple one, but one should look back, with admiration, to the early pioneers who were responsible for the development of the power shovel, the power dragline, the tractor, the scraper, and other mechanical equipment now used in the construction industry.

The Author believes that it was a William Smith Otis who, in 1836, at the age of 20, applied for a patent covering the first steam excavator—fore-runner of the modern power shovel. It was not until about 40 years later that a successful steam shovel appeared on the market, and later still—about 1905—that the first crawler track appeared.

During the first quarter of the present century, mechanical power in the field of construction gained momentum, spurred on, no doubt, by the advent of the petrol engine. The first World War set the stage for significant development; the alliance of the bulldozer with crawler tractors came about in 1923, and it was at about the same time that the Diesel engine made its appearance.

The development of heavy earth-moving equipment over the years made possible the rapid and economical construction of enormous volumes of work, not only in Great Britain but throughout the world. Much has been learned since 1938 about the economical use of equipment and its complicated maintenance, and the Author hopes that the Paper may provide some useful information on this subject.

Introduction

The Author is aware that many of the Institution members are actively engaged in, or responsible for, the direction of large organizations or undertakings connected with construction projects calling for the use of large earth-moving equipments of various makes and designs.

Comprehensive Papers have already been published concerning developments in the use and design of mechanical earth-moving plant and open-grabbing, relating to bridge and similar foundations. It is assumed

that the contents of these Papers will be applied by the reader and that no further reference is necessary.

The equipment discussed in this Paper is referred to by size only so far as excavators are concerned, and by class so far as tractors and other earth-moving equipments are concerned.

The object of this Paper is to convey to the reader problems which, in the Author's experience, have fundamental influence upon the economical use of heavy earth-moving equipment, and it is hoped that the general application to the whole field has not been lost through the endeavours to condense this expansive subject into broad aspects, rather than to indulge in detailed descriptions which would apply only to specific operations.

Application

The economic use of all types, makes, and sizes of earth-moving equipments in common use today must, or should, be related to production by way of the number of cubic yards of material which the owner or engineer has assumed he should be able to achieve per hour of operation from each production unit employed. The motive to purchase and operate equipment is based on economical considerations and it is essential to be able to interpret the performance and efficiency of earth-moving equipment in the terms of cost per cubic yard of material moved.

Where good judgement dictates the wisdom in choice and number of excavating units, together with whatever items of allied equipment are to be used in carrying out the project, the principles of earth moving and the elements, which may and indeed do affect performance, should be carefully considered.

The task of estimating probable performance of equipment calls for considerable practical experience in the field, and involves a careful analysis of all local factors existing or likely to arise on the project to be undertaken.

The economical and efficient movement of earth is as important as the fixing of shuttering and reinforcement, the mixing and placing of concrete, the driving of piles, etc., and, from the point of view of cost analysis, is often more important, owing to the relatively small units of measurements compared with the production of modern equipment. It is, in its execution, a matter of applying the correct tool for a specific purpose, operated by an efficient operator, as indeed is the case for any other trade within the civil engineering industries, with the exception that the tools used in earth moving are generally more expensive to acquire and cumbersome to convey; the Author suggests that the day is past when the chief engineer, the field engineer, the superintendent of works, the walking or principal foreman, or job ganger can call haphazardly upon his supply depots for major units of equipment, with-

out first considering some basic elements of the particular problem or job in hand.

It is assumed throughout that mechanical equipment is being used for the correct purpose. No justification for the use of mechanical aid is contemplated, but it is presumed that such aids, properly understood and applied, will maintain the required standard of production, with due consideration to age and condition.

Factors affecting the economic use and the maintenance of heavy earth-moving equipments today, may be summarized as follows :—

1. The human element.
2. Financial considerations.
3. Constructional considerations.
   (*a*) Job lay-out
   (*b*) Prospecting
   (*c*) Plant selection
   (*d*) Hours of operation
   (*e*) Seasons of the year
   (*f*) Cycle control.
4. Mechanical considerations and field maintenance.

The Human Element

However excellent may be the economic administrative control and the lay-out of any project calling for the use of heavy earth-moving equipment, the operators of such equipment can, at will, upset planned production.

In spite of the growth of mechanization within the civil engineering industries, it has remained an accepted custom to allow casual employees to take control of machinery. Whereas, in the past, this may have been justified in the handling of simple steam plant and small units of equipment such as pumps, mixers, etc., having simple controls, the principle should no longer be applied to the handling of complicated modern machinery and the specialized maintenance required. That such conditions have been tolerated up to date is no doubt because of the lack of appreciation of :

(*a*) the capital investment involved ;
(*b*) the rapid advance in size and development of mechanical equipment ; and
(*c*) the absence of additional training schemes or apprenticeship schemes for all machine operators.

It is seriously suggested that the time has not only arrived, but is indeed past, when consideration should be given to the setting up of a national system of training for machine operators, which should be of benefit to both the equipment owner and the operator.

It is appreciated that Service Departments introduced, during World War II, a scheme intended to train raw recruits in the arts of machine operation; unfortunately, in general, their training consisted largely of how to pull the right lever at the right time, as a study or survey of surplus-equipment disposals since the end of hostilities will adequately illustrate. This principle of training has been practised to a certain extent in America, where one school of thought has advocated that the operator of a machine should be directly concerned about the production only, and expert teams are employed solely on the daily maintenance and servicing of machines. The principle is workable only where machines can be grouped in numbers of, say, six to eight, in order to complete the full servicing per team, within a shift; but the system lacks flexibility and can be practised only where machines can be taken out of production in rota.

In the absence of a national system of training or apprenticeship covering machine operation, it falls today upon each employer or user to introduce into his own organization his own standard of training, to cover unit operation as well as a basic mechanical knowledge. The system adopted by the Author in his own organization, is designed to cover both operators and civil engineering staff who are in control of projects. This consists of a period in the maintenance-and-repair shops, a further period on the test ground or trial area and a comprehensive course of international instructional films. In this way, at least, a fundamental basic mechanical conception is instilled into intelligent individuals who are sufficiently keen to advance their knowledge of the economic operation and control of mechanical equipment, and the Author suggests that, in selecting trainees for machine operation, the individual's educational standard, which in some way or other must have a bearing on his general intelligence, is of paramount importance.

It is only fair and reasonable to state that equipment manufacturers are anxious to see their products operated by highly skilled technicians and are, at all times, ready to render every assistance in the training of operators. Many manufacturers run their own training centres.

There is adequate evidence of mechanical equipment being used up to the limits of its maximum structural load, with little consideration for prime movers and transmissions. This is a shortsighted policy, which is likely to lead to increased maintenance costs, loss of production hours, and reduction of the productive life of such equipment; often, advance preparation of overburden, or alternative handling methods, or the introduction of, for example, a rooter, could not only prevent damage, but could increase the production and thus remain an economical proposition, even with the additional cost of such measures. This is an instance where the experience and knowledge of the individual can ultimately affect the outcome of a project, and it will be realized from this how important it is that supervisory civil-engineering staff should themselves be in possession of basic mechanical knowledge.

Financial Considerations

The capital expenditure vested in excavating equipment will almost invariably exceed the total value of the job in hand. It is imperative, therefore, that practical considerations be coupled with sound financial policy in the selection of plant units, the salvage value of which depends almost entirely upon re-employment.

A reasonably accurate forecast of the salvage value of equipment, the number of working hours per year, and the number of years of employment, provides a figure for depreciation related to working hours or units of production. To this must be added an estimate of the cost of spare parts and fitting in respect of breakdowns, the cost of periodic complete overhauls, as well as a proportion of the cost of a central plant depot, all related to working hours or units of production. This figure varies considerably with different types and sizes of plant in accordance with the employability thereof, and consequently must affect the selection of equipment in relation to the project.

With a schedule of basic rates for various types and sizes of machinery thus obtained, the estimator will be in a position to forecast his actual running cost per unit, by adding his estimate of the cost of consumable stores, operators, field maintenance, etc., and can, thereby, provide comparative estimates for the various plant combinations which may be anticipated.

Secondary considerations are the cost of transportation and erection, the cost of provision of service installations such as field repair-and-maintenance depots, fuel installation and distribution, electric transformers or generating plant, the provision of " stand-by " plant for " key operations " where continuity of production is particularly important, and the various factors connected with local peculiarities and the scheduled progress for the works to be undertaken.

After the final decision has thus been made regarding the plant which is to be employed, with due consideration to constructional and mechanical aspects as outlined in the following paragraphs, the apportioning of general overheads and profit can be made, and it is wise to delay such apportionment to this stage, where the investment value of the plant finally chosen can be considered over the full extent of the project in hand.

Constructional Considerations

Job lay-out.—It is here that the site or job engineer is provided with an opportunity of expressing his opinion as to the sizes and combinations of units necessary to operate his project, upon the basic principle of economy plus efficiency.

It is appreciated that the site engineer's indent may not, at all times. be met by his employers or employing authority ; nevertheless, the Site Engineer should approach his earth-moving problems along three distinct lines.

(*a*) Production capacity of the primary production plant to be employed.
(*b*) Number and capacity of dependent subsidiary machines, such as hauling units, etc., necessary to keep the primary production units fully employed.
(*c*) Careful synchronization of all units employed in order to obtain minimum delay and maximum production.

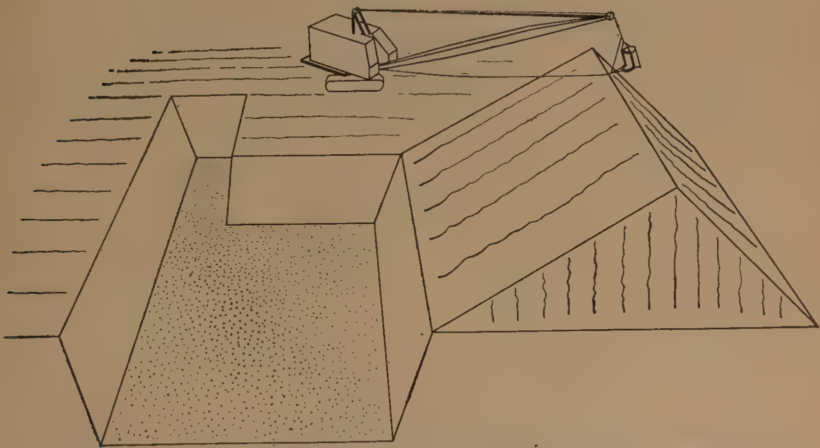
Maximum production can be maintained on any job only by careful advance planning. Economic earth moving should be regarded as a problem of team work, starting on the drawing board, worked out on the basis of ideal equipment combinations, then re-calculated, allowing for use of equipment available. A large percentage of present-day field engineers gained their initial experience in the use of heavy earth-moving equipments while serving in one or other of the armed services, during the time when the planned lay-out of site costs was not so important as it is today, and when large reserves of equipment could be called upon for short periods, if required. This conception must lead to spasmodic employment of units, with a consequential increase in the basic hourly cost, and cannot be applied to an organization basing its plant purchases and operation upon a sound financial basis.

The Author suggests that all planning operations should be based upon a 45-minute production hour, allowing for a production efficiency of 75 per cent. Successful economical operation of mechanical earth-moving equipments is closely linked with thorough planning of all operations, down to the smallest detail. Most of these operations can be broken down into a number of cycles, and the saving of effort and time on any part of such cycles will lessen fatigue on the machine operator and increase production. A close study, therefore, of all the details of a mechanical operation, which are influenced by either human judgement or any features which may be subject to judgement or control, such as is outlined under the following headings, must be the fundamentals upon which an engineer plans his job lay-out.

The initial job planning must be closely linked with the full details of the type of plant to be engaged, for example, capacity and vertical and horizontal operational limits for static plant; the turning radii, traction, and capacity of mobile units must affect the lay-out equally as much as the type of material to be excavated, as must the bulking factor and the angle of repose. It is not within the scope of this Paper to go into details of the various methods and plant combinations which are used for excavation under difficult conditions, such as excessive water-carrying strata, rock formation at varying depths, and other difficulties which may be encountered on many projects throughout the world. *Figs 1, 2, 3, 4,* and *5* are intended to serve only as general illustrations of deep excavations in reasonably homogeneous materials.

In general, it can be said that the job lay-out must be clean, consistent, and easy to understand by each man who is responsible for the economic operation of a mechanical unit. Complicated systems under which units work in restricted space close to each other, or mutually dependent upon each other, mean that a large amount of the operator's effort is engaged on watching other machines; consequently, this effort is lost to production in the form of fatigue, causing stoppages and, indeed, accidents, particularly where night shifts are operated.

Fig. 1



ORTHODOX "BOX CUT" METHOD USING A DRAGLINE WHERE A HIGH WALL SUPPORTS THE WEIGHT OF THE SPOIL BANK

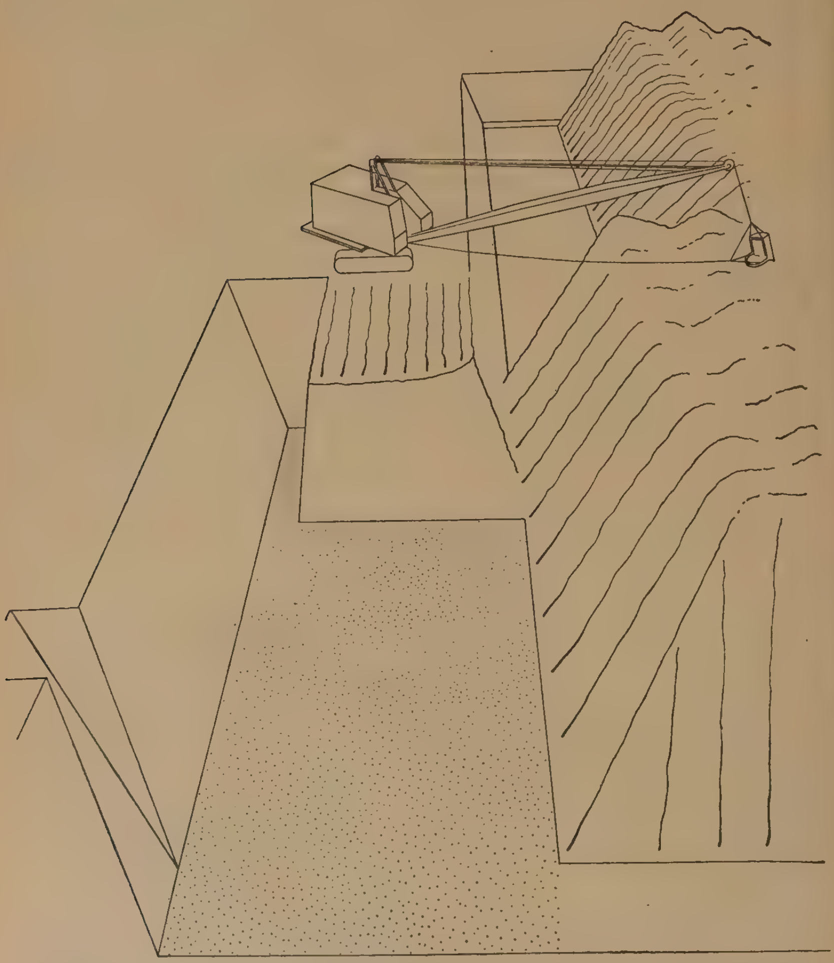
Prospecting.—In this Paper, the word "prospecting" is also intended to cover site investigation by way of inspection, combined with study of all available information provided by the principals responsible for the project being estimated or tendered for. There are numerous ways of approaching the problem of assessing one's risk in relation to large bulk-excavation works, and the procedure outlined below, may be considered as typical, rather than an exhaustive account of available methods.

In order to assess accurately the type of material which is to be excavated, handled, stacked, or used as consolidated fill, etc., it is necessary to carry out a thorough study of the strata, particularly where deep excavation is concerned. For this purpose, it is a useful measure, initially, to consult the geological surveys which are available superimposed on 6 inches = 1 mile or 1 inch = 1 mile Ordnance Sheets and, in certain cases, to peruse memoirs issued by the Department of Scientific and Industrial Research.

This initial investigation, when necessary, should be followed by accurate borings, preferably obtained by core-borings rigs, whereby

samples of the strata can be obtained and tested for hardness, fragmentation, and suitability for re-use as aggregate, fill, etc. Such field investigation is necessarily expensive and the extent to which it can be applied

Fig. 2

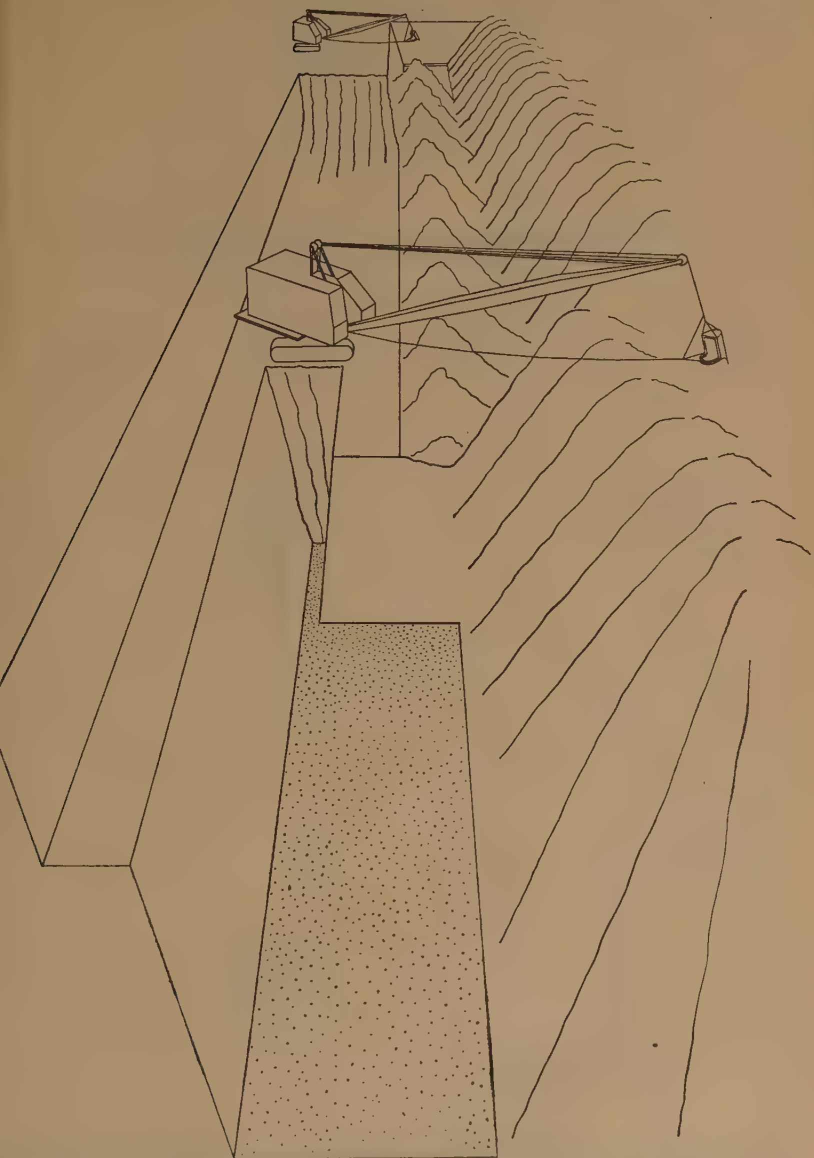


"Single Bench" Method by Dragline in Progressive Cut to Direct Fill

must be weighed against the importance and size of the earth-moving project to be undertaken.

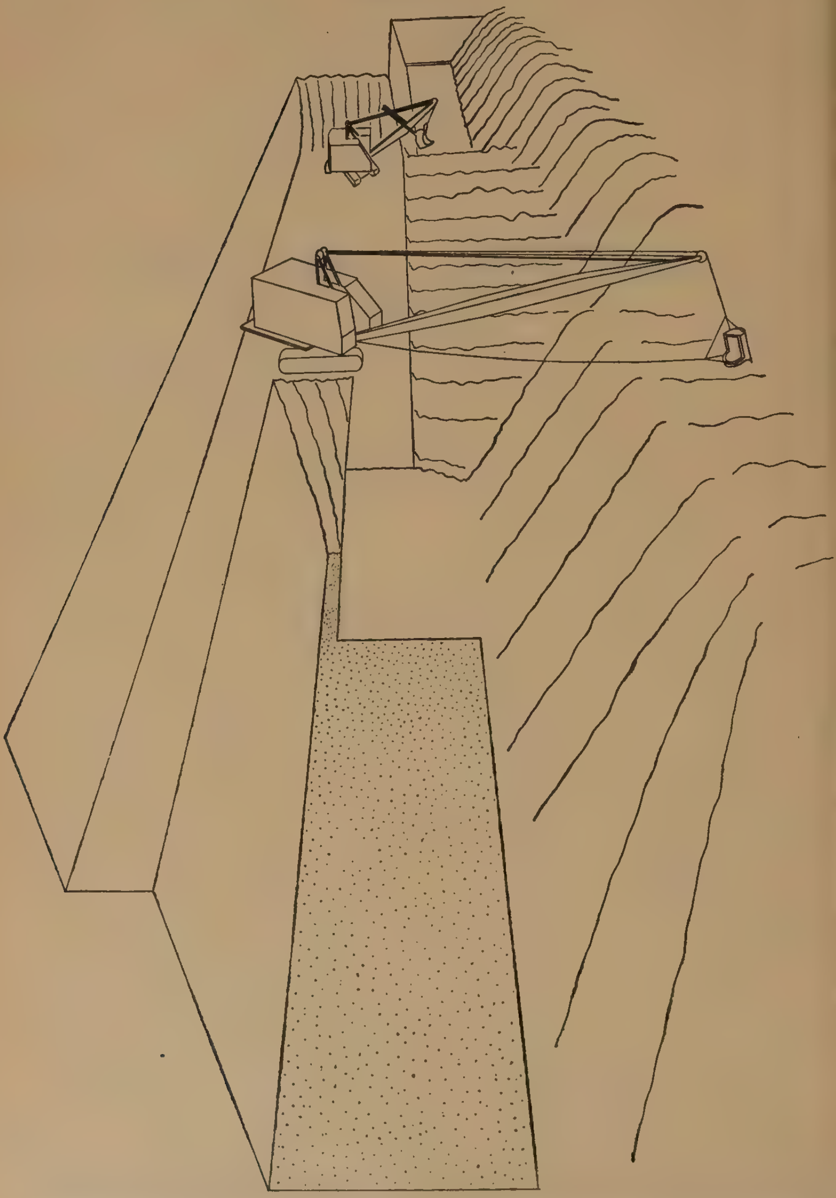
It is often possible to use information obtained from neighbouring quarries, cuttings, or shafts, and to relate this information to the working area through geophysical investigation of the continuity of the exposed

Fig. 3



"Double Bench" Method by Draglines in Progressive Cut to Direct Fill

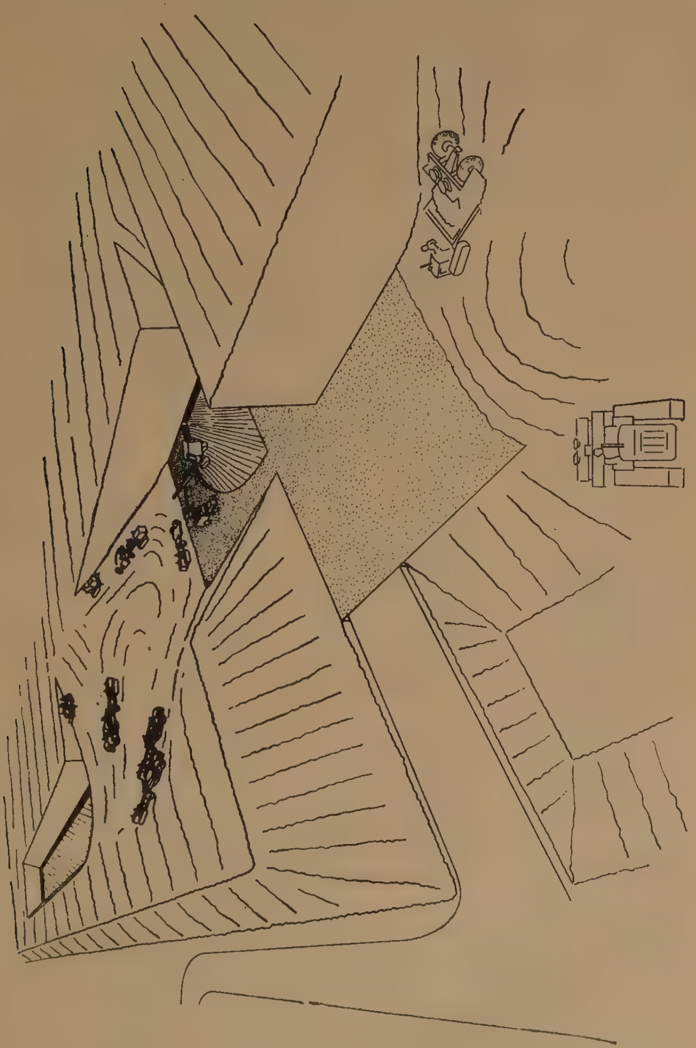
Fig. 4



"Double Bench" Method by Dragline and Face-Shovel in Progressive Cut to Direct Fill

strata by means of electrical resistivity, electro-magnetic, seismic, or gravimetric methods ; since these methods will, however, indicate only at which depth a variation in stratum takes place, it is necessary to identify the

Fig. 5



EXCAVATION BY TRACTOR/SCRAPER IN PROGRESSIVE CUT TO DIRECT FILL WITH CENTRAL ACCESS

strata by examination of an exposed face or by core boring, unless the geology of the area is particularly well known and it is considered safe to establish only the depth and continuity of known strata. Through each of these expedients, a measure is obtained of the depth at which a distinct

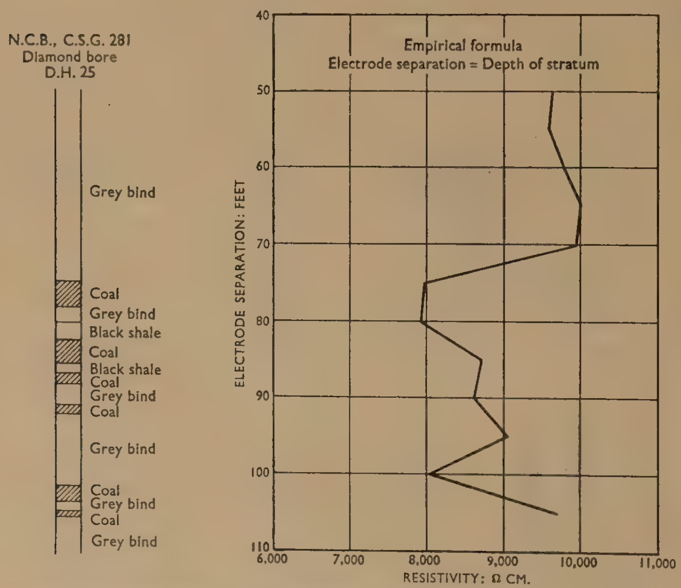
change in stratum takes place, thus, for example, the electrical resistivity survey is based on Wenner's relation :

$$\delta = 2\pi aR$$

for the resistivity, where a known current is passed through two electrodes in the ground at a distance of $3a$ and the potential fall is measured with a potentiometer connected to two further electrodes set in the ground between and in line with the first two at the third points (distance a apart).

The resistance R is calculated as $\frac{V}{I}$, where V is the measured voltage fall and I is the primary current and, as suggested by further experiments

Figs 6



ELECTRO-MAGNETIC OR GRAVIMETRIC METHODS OF PROSPECTING

carried out by Gish and Rooney, the resistivity δ can be considered as the average value of resistivity for the volume of ground between the two potential electrodes down to a depth a (equal to the electrode separation). The relation between a and δ can be plotted on a graph, the inflexions of which are interpreted as indicating a change in strata at the depth a. (See *Figs 6*.)

The intelligent use of the geophysical methods referred to can afford great saving in time and cost, and reasonably accurate results can be obtained provided they are related to a few " key core bore-holes " and provided, also, that the operator has a thorough knowledge of geological

structures, which is essential for accurate interpretation of the results obtained.

The detailed data obtained from the prospecting investigations are superimposed in plan and cross-section on the project drawings; the samples obtained may be subjected to further investigation and for this purpose can be arranged in the under-mentioned groups, reasonably related to the type or types of handling equipment required.

1. *Rock.*—Within the classification of rock for this purpose, fall all materials of a geological structure found in a monolithic condition at any moisture content, that is to say igneous rocks and sedimentary rocks, the latter group covering both cemented rocks and shales.

2. *Clay.*—Covering all plastic materials including vegetable soil.

3. *Sand and gravel.*—Examinations and tests carried out with these materials must naturally be relative to the size and type of machinery used; consequently, the classification of a material as rock and the index of hardness in connexion with penetration, may bear no relation to the usual geological standards, but are terms and figures relating to the behaviour of the material in its natural stratum and to the stresses which can be applied by various types of excavating machinery.

The types of tests and examinations which could be carried out are as follows:—

(*a*) *Penetration.*—This test may be carried out merely by driving a sharp-pointed knife into the sample and watching the crumbling or flaking, to ascertain the type of excavating plant which is required to handle the strata in situ, and whether advance preparation, such as breaking-up of the continuity of the strata by rooting or blasting, is required. It is insufficient to rely upon the penetration speed of a percussion drill (as possibly used during prospecting) to determine the penetration of rock, since in the case of sedimentary rocks, for example, a fine-grained sandstone may give a good penetration speed to a percussion drill compared with its reaction in the natural strata to the force of excavator teeth applied practically without impact. The presence of mica and the bedding of the rock (where this can be examined) as well as the thickness of strata and their position in the cut in relation to the excavating machinery, should also be considered in this connexion.

(*b*) *Fragmentation.*—If it is decided that advance preparation is necessary, fragmentation tests, taking the form of crushing of the sample and studying cleavage planes and binder, or alternatively test-blasting in situ, may be considered advisable.

(*c*) *Abrasion.*—A direct observation of the grain size and analysis of minerals should indicate if any special alloy or coating of

excavator teeth, jaws, and cutting blades, or other parts of machinery in contact with the material is required.

(*d*) *Plasticity.*—A determination of the plastic limit of clays and soils may be carried out to decide the usefulness of the available material for haul-road surfacing or as consolidated fill under the prevailing moisture conditions. Under this heading also, decisions may be made in relation to methods of dewatering silt and soft clays over areas where the transportation of materials is involved.

(*e*) *Grain size and bedding of sand.*—The investigation in connexion with subterranean water movements during excavation is made with a view to assessing with safety the angle of repose of temporary or final high walls in excavation, any shoring required, or lay-out of dewatering installations.

In cases where it is necessary to introduce advance preparation of rock overburden, the details and programme of the blasting process must be planned in advance, whether this is in tunnel, quarry, or large-scale earthworks.

Drilling, stemming, and blasting must be so timed as not to reduce the effective working hours and continuity of output of the primary excavating units. The method of drilling, size of blast holes, and placing of the charges are, in each case, a matter of experience to obtain the most suitable fragmentation, due consideration being given to the location of each project.

In almost all cases of large bulk-excavation works, thorough advance preparation of the material or strata to be removed considerably increases unit production.

Plant selection.—The range of plant and equipment as well as the merits of specific units and their prime movers, have been dealt with in previous Papers, as already mentioned.

The selection of plant for any project must, to a large extent, be based upon the considerations outlined in the foregoing paragraphs, but in most cases an even more far-sighted policy must be applied in the final decision, beyond the limits of the particular project in hand, even if such considerations may result in the selection of less suitable plant, or plant which may be adaptable to a wider range of operations than would otherwise be advocated, and it is here that a great deal of forethought and courage must be exercised in selecting the soundest investment commensurate with the general policy of the undertaking as a whole.

A further aspect which should be considered in this connexion is that of the standardization of plant and equipment, the main benefits of which are :—

(*a*) Interchangeability of equipment and the subsequent flexibility in operation.

(*b*) Reduction to the minimum of dormant capital tied up in stock of spare parts.

(*c*) The possibility of operating an exchange system of prime movers, thus eliminating costly field overhauls of engines.

(*d*) The free interchangeability of drivers in the field enabling them to be fully accustomed to the controls on all units.

(*e*) The use of the minimum number of grades of lubricants with the resultant elimination of mis-applications.

(*f*) The simplification of instructions for service and maintenance of units in the field.

The plant under consideration may fall within either of the following main groups of machinery involved in earth-moving operations :—

(1) The wholly static group which covers plant excavating in a fixed position and loading directly to spoil.

(2) The combined static and mobile groups, consisting of static excavators of group (1), and mobile transport units loaded by the excavator.

(3) The wholly mobile group covering such plant as dozers, tractor/scraper combinations, belt loaders with wagons, chain-bucket excavators, dredgers, etc.

The choice of a plant group depends mainly upon the nature of the operation involved and the type of material to be excavated, the ultimate use of same, the length of haul involved, as well as the depth of excavation itself.

Hours of operation.—Few equipment users ever agree as to the economic number of operational hours per shift.

The Author has caused a careful study to be maintained for a large number of years within his own organization, covering all types of manually-operated equipment, ranging from the smallest to the largest units in use, in order that reasonably accurate average production figures could be assessed for each unit.

Manufacturers' production figures are not reliable, although prepared and compiled in all good faith, since, it is suggested, these figures are usually obtained on a test ground, while moving ideal material under ideal conditions, and with new equipment.

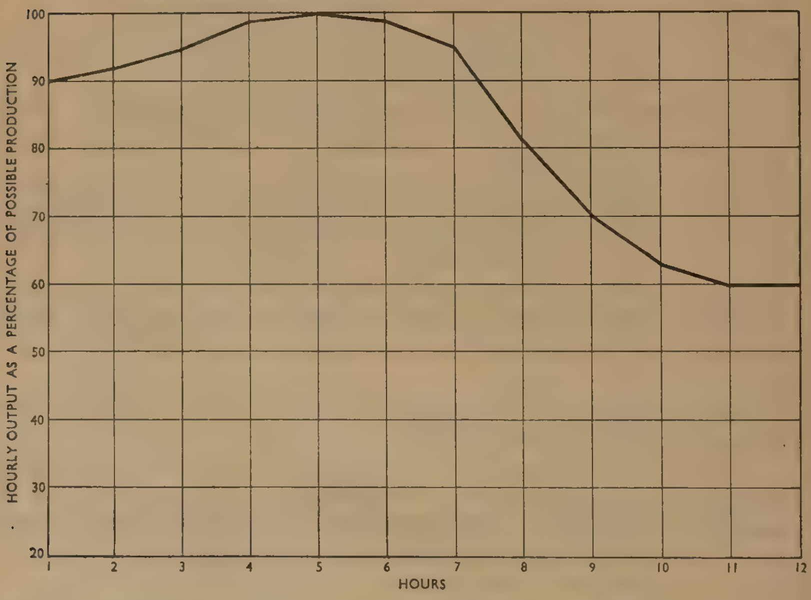
It should be appreciated that all mechanical equipments, like human beings, suffer from fatigue. This is not generally recognized by the average field or site engineer owing to lack of mechanical experience or mechanical knowledge.

The length of shift and number of shifts to be worked upon each project, requires careful consideration. Length of shifts should be adjusted to give ample opportunity for the efficient servicing of machines, although a certain latitude is often exercised in order that servicing periods for units working interdependently may coincide. It is important

also to consider well timed meal breaks, and to plan such breaks with the minimum of delay in working time, through the introduction of canteen cars, or other mobile aids. These breaks, if properly organized, will reduce industrial fatigue of the operators and have quite definite beneficial effects upon production.

The graph shown in *Fig. 7* has been compiled from a number of records for various types of machines. These records are largely based on spot checks and approximations. All the records show the consistent tendency as shown on the graph, which may serve as a useful guide, indicating the

Fig. 7



Graph showing how the Length of Shift affects Output

variation of production per hour progressively throughout a 12-hour shift, after having eliminated the effects of meal breaks. It will be noted from this graph that there is a distinct fall in productivity per hour after 8 working hours, which may be considered an optimum length of any shift.

The number of shifts to be worked is largely a matter of policy with due consideration to the number of years over which it is necessary to depreciate equipment. It is generally recognized, however, that on night shifts only, approximately 70 per cent of the day-shift production is obtained; the reduced productivity is attributed to psychological causes and restricted vision.

Seasons of the year.—It is recognized that in the main, employing authorities are encouraged to place their major works during the winter season from the point of view of maintaining seasonal employment. This policy may be sound; nevertheless, works entailing earth-moving should be planned to go into full production in say, March or early April of each year, and whenever possible, to shut down completely by the end of November—the winter or rainy season being set aside for annual overhaul.

The productivity of earth-moving operations is largely governed by the rainfall; this is particularly significant where mobile plant is concerned, and it should be borne in mind that mobile plant is not only affected during the actual rainfall, but for a period following, while haul-roads and dumps are being dried out and made passable. A close study of the average rainfall over the various seasons for the area in which the operation is being planned, and the corresponding scheduling of operations with a view to confining the activities, so far as possible, to static plant during wet seasons, will reduce the cost of surface drainage and maintenance of haulage roads.

Wherever possible, excavations and spoil dumps should be planned to be self-draining, or it may be considered that the whole of the excavation area could usefully be surface-drained or well-point drained, as may be necessary. It is particularly important that due forethought is exercised in the surface-drainage of plastic materials (clays and soil) during wet seasons. Unrestricted movement of surface water will endanger temporary high walls in excavation; it will reduce the angle of repose of wet material in dumps, with the possible consequence of enforced re-handling of the material, and, in the case of static plant, may affect the access to each unit of fuel supplies and other consumable stores. Where mobile plant or transport is employed during the wet seasons, special care must be taken in the selection of transport routes or haul-roads, the materials used for surfacing of same, and in the drainage thereof.

On the other hand, during the dry season, problems such as excessive dust on haul-roads may arise with subsequent reduced visibility for drivers of transport vehicles, increased fatigue, accidents, and delays. Under such circumstances, it is expedient for maintenance of production, to employ water-spray wagons, and such a measure will, in addition, prove beneficial for the maintenance of temporary haul-road surfaces, by retaining on these an optimum moisture content. In the case of tractor/scraper operations during particularly dry seasons on clay, allowance must be made for a rooter to be engaged to overcome the hardening of the material to be excavated and the subsequent reduction in output. The Author suggests that on all excavation contracts of reasonable size Autopatrols or power graders, are most useful pieces of equipment—their usefulness is not yet fully appreciated by the modern engineer.

Cycle control.—In the execution of any earth-moving project, the

control of length and frequency of the cycles into which each operation can be broken down is entirely in the hands of the supervisory staff in the field. As suggested earlier, there are in most cycles of mechanical operations, elements which are influenced by human judgement or by features which may be subjected to adjustment, and it is here that the experience, intelligence, and foresight of the field supervisory staff, through constant stop-watch checking and adjustment, ultimately govern production and cost.

It is often the most insignificant part of a production cycle on which the greatest saving can be effected, and this percentage of saving on the full cycle is directly related to an increase in production and a saving in cost.

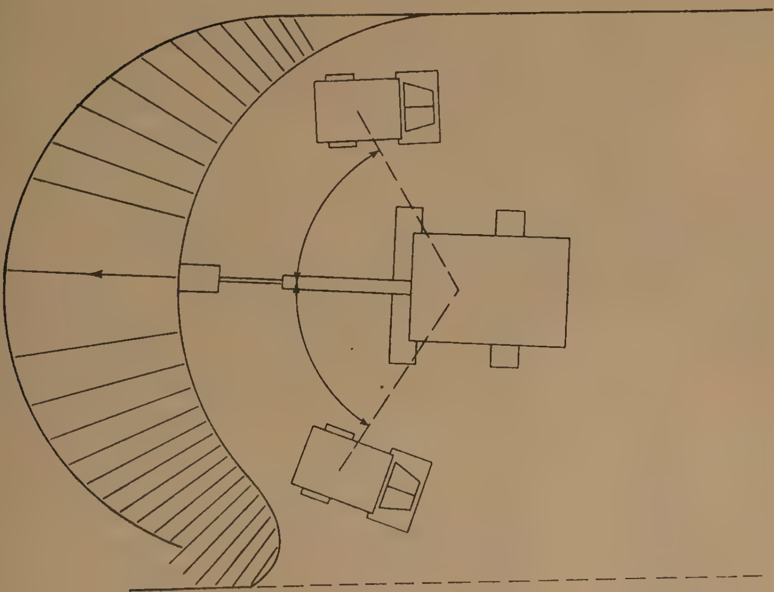
The following examples and suggestions are intended to indicate some typical contributors :—

(1) *Static plant.*—The cycles of static plant, when operated independently, are simple to control; there is no co-ordination required, and adjustments are confined to the capabilities of a single unit and its operator. A type of unit commonly operated thus is the dragline and for this machine particular attention should be given in the first instance to vertical lift and angle of swing from excavation to deposit. It is tempting to use a short jib and a large bucket, and to excavate as deep a cut as possible, but it will be seen from *Figs 1*, *2*, *3*, and *4*, that the effective dumping radius is drastically reduced with increase in depth. Taking the angle of repose of the loose deposit at approximately 45 degrees it is clear that the required dumping radius must be equal to the full height of the tip (including bulkage of, say, 20 per cent), plus the safe distance from the machine to the high wall, and the projected distance of the high-wall slope, both of which increase with the depth of cut. For economic working, the depth of cut should not exceed half the jib length; deeper cuts should be worked on the bench methods as illustrated, whereby stabilization of the high wall is obtained and the lower-bench machines can get closer to the deposit. The additional vertical lift required from the lower-bench machine is easily outweighed by the increased efficiency of the top-bench machines and the reduction of re-handled spoil. The effect of the slewing angle is illustrated in *Example 2* below.

Where static plant is operated in combination with other static plant or with mobile plant, their interdependence must be considered. There are endless numbers of combinations of various types and sizes of plant depending upon each other in varying degrees, but it is almost invariably possible to select one unit as the primary machine upon which the whole production depends. This machine will usually be an excavator and upon the largest possible production of this machine working at full efficiency must all secondary units be selected in size and type, as must also the planning of progress and sequence. A simple example is illustrated in *Example 1* below.

Example 1.—In this example, illustrated in *Fig. 8*, excavation is being carried out by a face-shovel loading into transport, which could move only within the width of the cut. On the original lay-out, the width of the cut was half of that shown, and only one transport vehicle at a time could move into loading position under the shovel. With the amended arrangement, however, as shown on *Fig. 8* where the width of the cut is doubled and transport can move into loading position on either side, the loading time for the shovel is practically continuous and an increase in production of 12 per cent thus obtained.

Fig. 8



ECONOMIC FACE-SHOVEL LOADING, REFERRED TO IN EXAMPLE 1

Example 2.—In the example illustrated in *Fig. 9*, a dragline is excavating and loading directly to spoil, the movement of excavated material from cut to tip is arranged along the dotted line at an angle of 65 degrees to the direction of the cut instead of at 90 degrees : the result is that the excavating dragline jib moved, between cut and tip, an angle of approximately 45 degrees against the original angle of 90 degrees in a 40-foot-deep cut. The increase in production under actual

working conditions adopting this arrangement was 8 per cent, and it was found that the saving amply allowed for the additional double handling which would have to take place at the end of each cut.

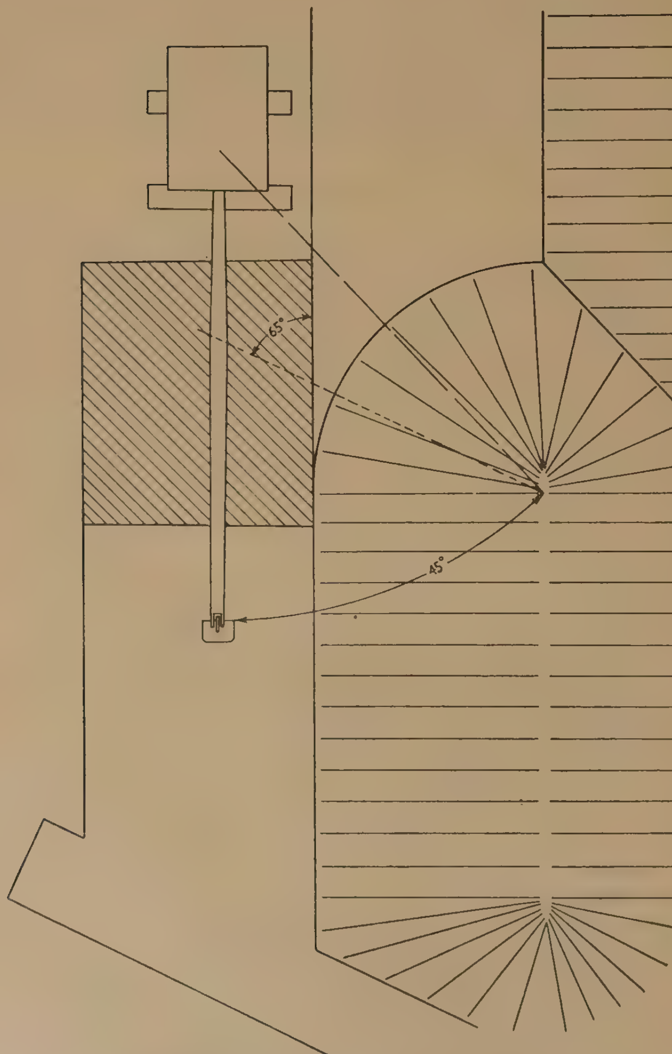


Fig. 9

Diagram showing Uneconomical Positioning for use of Dragline, referred to in Example 2

(2) *Mobile plant.*—The major portion of mobile plant engaged in earth-moving operations is that part engaged in transportation of excavated

aaterials, and in this respect the most important consideration is the aechanical effort required to convey a specified load at a specified speed n order to maintain 100-per-cent efficiency from the basic excavator.

The conveyance may be barge, rail truck, conveyor belt, or rubber-ired or tracked transport; the motive power required must be sufficient o accelerate the full load to a given speed, and maintain it against the otal resistance from all sources. For each type of conveyance, design oads have been fixed by the makers in respect of a range of working onditions and speeds, taking into consideration constant frictional losses, uch as internal friction, deformation in conveyor belting, rolling resist-ance on rails for various gradients and loads; whilst in the case of indepen-lent transport units operating on temporary construction roads, such ariable combinations of circumstances may be encountered that an nalysis must be made in each individual case. For this purpose it is onvenient if the reactions to be overcome from varying circumstances re tabulated in expressions which can be directly compared with available "rim-pull" or "drawbar-pull" from the towing unit or the vehicle tself. The analysis can be arranged under the three headings :—

(*a*) Rolling resistance
(*b*) Grade resistance
(*c*) Coefficient of traction.

(*a*) *Rolling resistance.*—The rolling resistance has been defined as the orce necessary to maintain the constant speed of a vehicle over a hori-ontal surface. Accepting in the first instance the proximation that this orce is constant for the limited range of speeds, which had been practicable n earth-moving operations up to date, the force thus defined would be he sum of the following factors :—

(i) Internal friction in the vehicle.
(ii) The effort expended in the deformation of the tires on an inflexible smooth road.
(iii) The effort expended in the deformation of the springs and tires (additional to (ii) above) on undulated road surface.
(iv) Compaction and displacement of the material constituting the road.
(v) The effort expended in the vertical movements of the centre of gravity of the vehicle, due to undulations in the road surface.

Of these, the sum of (i) and (ii) is a constant for any particular make nd capacity of vehicle (tires being at a specific tire pressure), and it is ossible to provide suitable constants for the full range of vehicles, related o gross loads. The sum of factors (iii), (iv), and (v) can be expressed or the various types and conditions of road construction or natural urfaces, similarly related to gross load, with a correction factor to allow or variations in (iii) for different constructions.

The figure thus obtained for the total rolling resistance would be applicable, not only at constant speed but, with good approximation, can be added also to the force which is required for acceleration within the range of any one gear-ratio.

The Author is well aware that no reliable system has yet been developed for the whole range of earth-moving transport, which would enable the planning engineer to give a reasonably accurate forecast of the rolling resistance resulting from every given set of circumstances. The problem is complex and a vast amount of recorded tests are required, as will be realized when it is appreciated that changing to a different make of one complete set of tires on a large haulage vehicle affected the rolling resistance by as much as the equivalent of a 4-per-cent adverse grade. The influence of the known and recognizable features, however, is so great, that it is considered proper to establish their existence.

An important contribution to the solution of this problem was made, in respect of one well-known make of transport vehicle, in a series of lectures by Kenneth F. Park at the graduate school of engineering, Harvard University, in 1942. In this case all the above factors (i) to (v) were summarily expressed in terms of lb. per U.S. ton (2,000 lb.) of gross load for various road surfaces, and the resultant force was directly related to "rim-pull" or "drawbar-pull" of the towing unit. Although this method is a rough approximation, it has been developed from a large amount of practical data, and has produced surprisingly accurate results even 10 years later with improved designs of the same type of vehicles.

An example illustrating the magnitude of the rolling resistance is the conversion of a 200-yard-long rough natural haulage track for tractor/scraper combinations, which, after being built up with suitable shale, drained, and maintained by a grader patrol, allowed an increase in the average speed of haul from 3·1 to 3·7 miles per hour. This improvement represented a 14-per-cent increase in the number of whole cycles per unit or in output per hour, which amply justified, in this instance, the extra cost expended in reconstruction and maintenance of the haulage road, even ignoring the effect of reduced wear on the plant.

(*b*) *Grade resistance.*—The additional force which is required to maintain constant speed of a vehicle on an adverse gradient over and above the force necessary to overcome the rolling resistance, is the projection of the gross-load gravity vector on to the sloping surface or: $W \sin a$ (W denoting the gross load and a the angle of gradient to the horizontal). On the other hand, on a favourable gradient, this force will add to the power of the towing unit, and in the wholly mobile group of excavating plant full use should be made thereof in planning the excavation so far as possible, "down hill." In the case of, for example, tractor/scrapers, an expedient such as this would either increase the speed of loading and thus reduce the time taken per cycle, or alternatively enable a larger

scraper to be used behind the towing unit, thus increasing production per cycle of operation.

On the haul-roads and particularly the more permanent type of haul roads, the gradient should, if possible, be so adjusted that the minimum number of gear changes are required and the best possible performance within the range of any one gear can be obtained under prevailing weather conditions. To this end, the steepest gradient at which full tractive effort can be obtained in the lowest gear with the maximum load and under the most adverse weather conditions should be determined; the necessary climb should then be obtained over the shortest possible continuous length of haul-road at the maximum gradient, the remaining haul-road being determined similarly for the highest possible gear. Such an arrangement will utilize the full power of the towing unit and thus prove the fastest way of lifting a given load to a certain height. In the case of rubber-tired units, it may be necessary on the return journey to seek an alternative route to the steepest gradient in order to avoid excessive wear on clutches or brakes and minimize the risk of accidents in greasy ground conditions.

Resistances encountered in vehicular earth-moving as outlined in this and the previous sections have been treated in general without specific reference to any particular type or make of transport unit, and although it is not yet possible to refer to practical schedules for these resistances which could be used in calculations for the full range of mobile or static earth-moving equipment, the Author hopes that an indication of the scope and the needs which present themselves has been given. Until such tables or schedules have been compiled, from practical tests, he would advise the reader to make use of such figures which are available and to which reference has been made, and to adjust these figures to his own circumstances or particular project with which he is confronted.

(c) *Coefficient of traction.*—The performance of a haulage unit depends ultimately upon its tractive effect. So far, reference has been made only to "drawbar-pull" or "rim-pull," but whether or not the towing unit will be able to develop the maximum torque for which this "pull" has been listed, depends on the friction between tracks or tires and the surface over which the movement takes place.

Thus, if the load or reaction is steadily increased, a point will be reached where either the motive power of the prime mover of the towing unit will stall or the unit will slip on the surface. Stalling will take place provided the surface-to-track (or tire) friction is large enough, at a point where the reaction exceeds the force developed at maximum torque, whereas slipping will occur if this friction is insufficient for the development of maximum torque of the motive power.

A measure for the first condition is provided in the figures for maximum drawbar- or rim-pull listed for each gear by the manufacturers and an

expression for the coefficient of friction necessary to produce this condition is :—

$$\frac{\text{Lateral force}}{\text{Normal reaction}} = \frac{\text{Maximum drawbar- or rim-pull}}{\text{Weight of towing unit on tracks or driving wheels}}$$

which may be quoted as the critical coefficient of friction.

On the other hand, if an expression of the static coefficient of friction can be tabulated for various surfaces and conditions thereof in relation to the most common types of cleated tracks and rubber tires, the necessary requirement for avoiding slip would be that the figure selected from such a schedule should be larger than the critical friction mentioned above; in other words, it would merely be a matter of multiplying the coefficient of friction (related to surfaces) by the weight applied by the towing unit on its tracks or driving wheels, and ascertaining that the resultant product exceeds the listed drawbar- or rim-pull for the required gear.

The procedure outlined here, although giving useful practical results, is not strictly correct, since the friction which is considered is not a clean friction; thus for a track-laying unit with normal grouser tracks, the coefficient of friction would vary considerably with the grousers' ability to "dig in" and, therefore, to a certain extent, would be dependent upon the relation between weight and area of track of the unit. For example, on a concrete road the coefficient of friction would be that of steel to concrete, whereas on a soft clay surface, it would be that obtained between the clay strips held between the grousers of the track, and the remaining body of clay. Also in respect of rubber-tired units, the presence of tire creep, particularly on hard surfaces, complicates the expression of the coefficient of friction.

Nevertheless, an approximation can be obtained which gives sufficient accuracy for the use suggested in this section, but it is important that the figures for the coefficient of friction which are being used have been obtained through practical tests. Attempts have been made to compile schedules of such figures by American manufacturers of rubber-tired equipment, and as a reasonably good approximation, these figures can be applied also to track-laying units by increasing them by 50 per cent.

Mechanical Considerations and Field Maintenance

It is assumed that heavy earth-moving equipments of all types are well known within the civil engineering industry, but it should be appreciated that the principal mechanical aids of the construction industry have really developed over the past 20 years.

The prime mover in an item of mechanical equipment is nothing more than a piece of metal with a few holes mechanically drilled or bored therein, and a few pistons operating by way of compression.

It may be of interest to note that the "diesel" engine gets its name

from a Dr Diesel, who provided the formula for the fore-runner of existing diesel engines not more than half a century ago.

Throughout the world, many standards relating to diesel-engine construction have been published. It was about 1930 that a group of engineers representing manufacturers of diesel engines, collaborated to produce documents which might be of interest to the diesel-engine user and the civil engineering industry as a whole. These standards, revised and republished in 1935, 1946, and again in 1951, are entitled "*Standard Practices for Low and Medium Speed Diesel Engines*" and cover the following aspects :—

(*a*) Definition.
(*b*) Performance.
(*c*) Diesel engine construction.
(*d*) Governors and speed regulation.
(*e*) Torsional vibration.
(*f*) Oil characteristics.
(*g*) Field test code.
(*h*) Operation and maintenance.

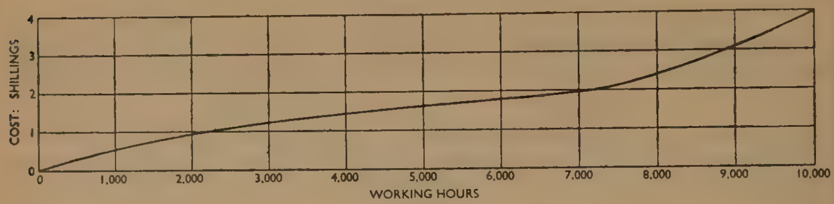
It will be appreciated that the selection, purchase, testing, operation, and maintenance of diesel-operated plant, at times calling for the use of dual prime movers and associated equipments, should be under the guidance of a qualified mechanical engineer. He is, today, equally as important in the construction industry as the site engineer, and he should have gained the necessary experience in the field maintenance of large fleets of equipment.

The development of prime movers over the past 20-25 years, in relation to construction equipment, has created a necessary interest in relation to mechanical engineering from the point of view of field maintenance. The developments which have taken place call for not only the employment of, but also the creation of, efficiency in the maintenance-and-repair organization of the user. It may be remembered that a quarter of a century ago, the maintenance staff were referred to as the "black gang."

Figs 10 to *17* indicate, for the various sizes of equipment shown, the cost of field maintenance in relation to the average physical operational hours worked. These graphs should not be considered as indicating equipment depreciation; the cost figures shown take into account the average overhead expenses attached to the normal field-repair organization.

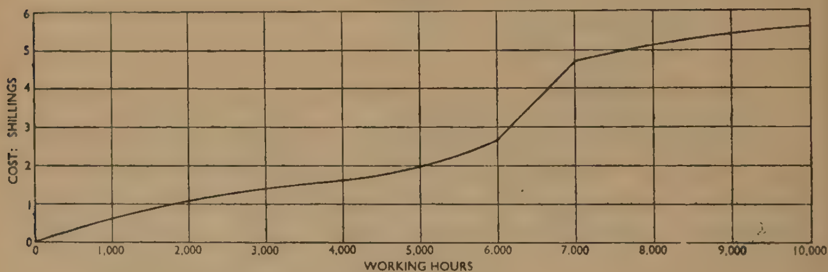
Field servicing of equipment, if controlled and properly carried out at regular intervals, should reduce mechanical breakdowns. Site Engineers, often referred to as "Agents," who are responsible for the direct supervision of contract sites and the employment of people thereon, are today of the opinion that mechanization requires little or no attention. Machine servicing on contract sites, if properly understood by the supervisory staff, is most important, and if regularly controlled, will do much to create better overall performance, correspondingly reducing site costs.

Fig. 10



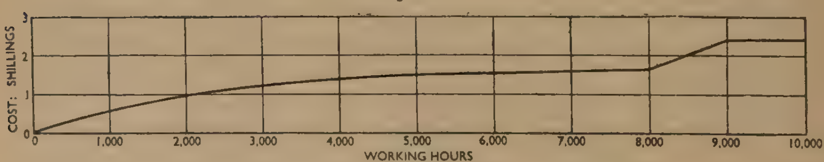
Class I Tractor

Fig. 11



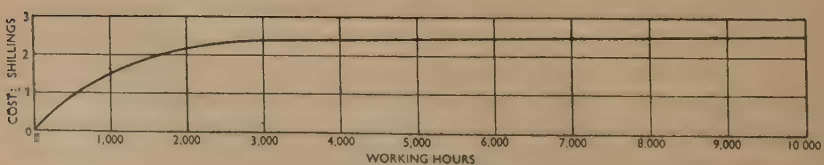
Class II Tractor

Fig. 12



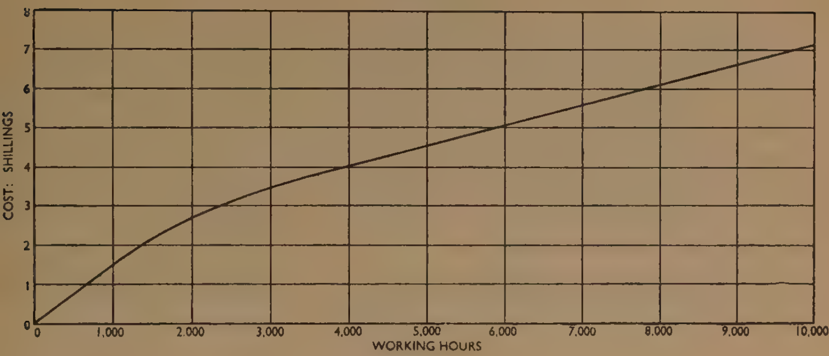
⅝-cubic-yard Excavator

Fig. 13



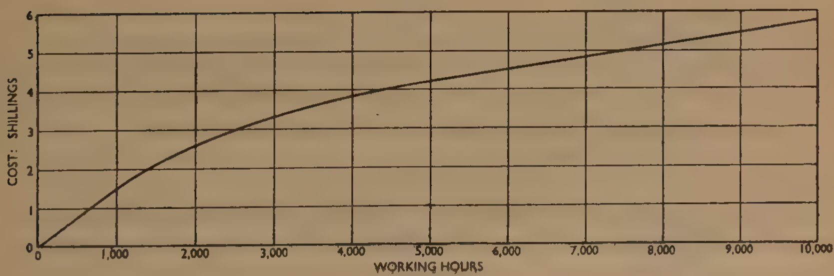
1½-cubic-yard Excavator

Fig. 14



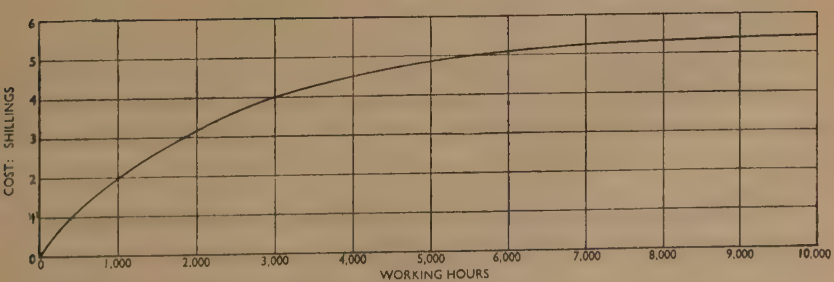
2-CUBIC-YARD EXCAVATOR

Fig. 15



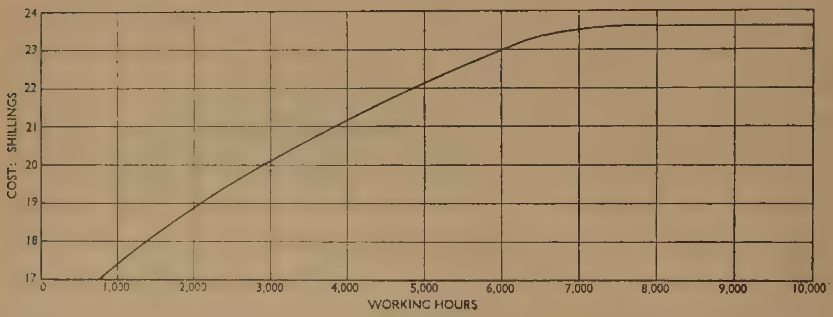
3½-CUBIC-YARD EXCAVATOR

Fig. 16



16/60 TRENCH EXCAVATOR

Fig. 17



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Site machine servicing is today regarded as the responsibility of the machine operator. From experience, however, it is clearly indicated that the machine operator is not generally controlled so far as the servicing of his unit is concerned.

Intelligent operators who have gained sufficient experience to enable them to treat the units under their control with respect are today few and far between. It is suggested that field-service units should be controlled by an experienced mechanical engineer or supervisor, who should accept the responsibility for the engagement of the maintenance staff.

Assuming that the mechanical engineer or supervisor has a sufficiently wide experience of heavy earth-moving equipment, he should be in a position to plan the field organization required to take care of the equipment under his control. The method used in the Author's organization, over a long period of time covering the life of mechanical equipment, is to record the following factors :—

(*a*) Valuation record covering depreciation.
(*b*) Machine efficiency.
(*c*) Maintenance record.
(*d*) Revenue from earnings.
(*e*) Machine history record.

The value of plant records should, over a period of years, be measured by their accuracy in relation to accountancy, and the information derived from such records can, at all times, prove most useful in the preparation of competitive estimates.

The Paper is accompanied by thirteen sheets of diagrams from which the Figures in the text have been prepared.

Discussion

Mr R. M. Wynne-Edwards observed that the Author had made a special study for many years of muck-shifting by machine, and the Paper, therefore, gave an expert's view of the problem. It was an important problem, because the present-day almost universal use of the machine for excavating had made changes in the carrying out of civil engineering works which were so far-reaching that their consequences were only partly realized. A great deal of civil engineering work consisted in moving earth, or some other material, from one place to another, and for more than a hundred years it had grown up round the performance of the navvy. An industry had developed, adapting itself to the execution of work in that way, in which the gangs of navvies with their gangers—often on piece-work—used to perform prodigious tasks; the structure of job management had been built up accordingly.

Today the navvy had gone, and the machines which had replaced him behaved in quite a different way, requiring new techniques in management and a new structure of job organization. The changes had happened so comparatively recently and so rapidly that the effects were only now being observed and learned. For one thing, the navvies had been many and the machines, each doing the work of many men, were few. Time-keepers used to keep very careful check on the men's arrival and departure, and would go round the job at intervals to see that the men were at work. Today it was more important to keep the machine's time (since it could do in a minute what a navvy might have taken an hour or more to do) and to see that the machine started and finished on time and kept going all day. Whereas they had been concerned with the performance and productivity of the navvy, they should now be concerned with the same factors in respect of the machine.

Mr Wynne-Edwards felt that it was imperative that those who were, or who hoped to be, concerned with carrying out large civil engineering works should learn how to make the best use of machines. Training in what was commonly thought of as the civil side of engineering was not, in his opinion, enough, and he thought that those whose aim it was to be contractors' agents should learn much more about the mechanical side; there was a good deal of talk about "productivity per man-hour", but what was really meant was "productivity per man-*plus*-machine-hour." Engineers who had taken a mechanical degree, and who had had training on the machine and its care and performance, were just as likely to make good contractors' agents as those trained on purely civil engineering lines. Mr Wynne-Edwards hoped that more mechanical engineers would enter the industry, and believed that that would improve its efficiency.

Mr J. R. Caseley said that the Author had had to deal with his subject very largely on general principles, and had done so very well. He had set out on p. 59, presumably in order of importance, the main factors

in the operation of earth-moving machines and had put the human element first. Mr Caseley agreed with that. The whole of the team employed in the operation, maintenance, and repair of the machinery, together with the planner or engineer who laid out the job and decided on the type of machinery to be used, were of equal importance, and if any man or body of men in that team failed in his or their duty and did not do the right thing in the right way in a co-operative spirit, the productivity of the machine, which was all-important, would be lost.

Fig. 7 seemed to indicate that when the operator, or anyone else concerned with the productivity of a machine, was employed for longer than a certain period—which appeared to be about 7 hours—there would be a rapid decline in output. That was also Mr Caseley's opinion, gained from personal experience. It was asking too much, he thought, to expect a man who was driving a modern machine, of the type and size common in Great Britain, to work an 8-hour shift and then do 4 hours' overtime. It would be remarkable if the curve in *Fig. 7* showed anything but a rapid fall in output.

Regarding the very large machines used in the United States, where it was essential to get the maximum output from every minute of their work, because they represented such a huge capital investment and the expense of running them was so great, he had been told that a system, found to be the most suitable, had been evolved. It meant working on a $22\frac{1}{2}$-hour cycle daily for 6 days ; the first shift worked from 7 a.m. to 2.30 p.m., the second from 2.30 p.m. (without a break between shifts) to 10 p.m., and the third from 10 p.m. to 5.30 a.m. There was no reason why the machine in question, a large electrically operated machine, should not work for the full 24 hours, the break from 5.30 a.m. to 7 a.m. not being for the purpose of carrying out any servicing, but largely because it had been found that at the end of a night shift a man's efficiency dropped, and it had been found better to stop the whole job for $1\frac{1}{2}$ hours, and have three $7\frac{1}{2}$-hour shifts instead of three 8-hour shifts. On Sunday, only one shift was worked, during which maintenance by the gang responsible was carried out ; no operators were employed on that shift. Presumably the Author intended the graph in *Fig. 7* to represent a shift worked by one operator, but perhaps he would confirm that in his reply.

The Author had made some very interesting remarks on the method of maintenance of the machinery. Everybody would be familiar with instances of where a machine was "flogged" because the operator was on piecework, and, when something broke, the operator, the banksman, and the greaser were expected to turn themselves suddenly into plant repairers or fitters. That was certainly wrong. An efficient car driver or racing motorist did not necessarily have to be a good mechanic, and it was bad organization to put a very expensive piece of machinery into the hands of an improvised maintenance gang of that kind.

The other important point about the human element was that unless

mechanical means were properly planned and understood—and that experience could be gained only in practice so that the right plant was used for the right job in the right way—the use of machinery, instead of being an economy in the moving of earth, would become just the reverse, a load round the industry's neck, and would probably involve the loss of a great deal of money.

The Author had omitted to deal with ground preparation. All earth-moving involved the very important element of digging, and the type of plant and the method of its use depended a great deal upon that one element. It was essential to undertake thorough prospecting and to decide on a preparation plan of drilling and blasting. That was a subject in itself, and the Author could not be expected to give any details about it, but it was an important item to bear in mind and came high in order of importance in connexion with the use of mechanical equipment for moving earth.

It was most important that civil engineers interested in the development of new methods of earth-moving, which was going ahead very rapidly on the lines followed in America, should take advantage of the advice of people such as those in the Author's organization and incorporate some form of apprenticeship or practical training with the normal theoretical training of a civil engineer.

Mr Charles Willment remarked that his own experience of muck-shifting went back to the construction of the Panama Canal, where steam shovels had been used to load into side-tipping wagons, and as much as a mile of railway had been laid in one day to get rid of the muck. When, in 1909, they had reached a figure of 250,000 cubic yards a month, they had felt " on top of the world," and he had been chosen to see Colonel Goethals, the civil engineer in charge of the work, and ask him for payment for wet time—which had been granted. Mr Willment said that it might be of interest to mention that there had been trouble there with a hill which had sunk and come up, as it were, through the bottom of the cut, and referred to a site in Whitehall where the consulting engineers had thought that something of the same sort might happen, since the work had been 50 feet below the bed of the River Thames.

Whilst there was nothing that Mr Willment could add to the Paper on the technical side, on the psychological side he would like to emphasize, as the result of long experience, the importance of getting to know one's operators and using a little of the personal touch. One of the most valuable suggestions in the Paper was that the more the civil engineer knew about the mechanical side of the machines which he used, the better the results he would get from the operators. There were many operators who would take advantage of his ignorance, but they would respect a man who could show that he knew how to operate the machines and could even reduce the time-cycle for their operations. Times had changed since the piecework rate of $2d.$ per yard was paid for loading sand into barges

on the Thames and 2½*d.* per yard for loading ballast. Some of those barges were still there, but those rates were not.

The Author's advice to load downhill was most valuable for all scraper work. Mr Willment had studied the whole Paper with great care, because he was not too old to learn. There were still problems in muck-shifting which caused great difficulty—he was facing one himself at the moment. On one particular job, the engineer to the authority concerned had told him "We will show you how to dig this; we know the ground round here." Using the number of men that engineer employed, two pipes were laid in one day, and the cost had been £18 per yard. There was a lesson in that for civil engineers.

Mr J. L. Ritchie, who said that he looked at the subject from the point of view of the plant manufacturer, emphasized that the Paper advocated what the manufacturers had been preaching to the civil engineer for years, namely, that if he wanted to do things economically—and who in the contracting world did not ?—he was not throwing money away by taking machines out for maintenance, but was in fact saving money. The Author had pointed out that it paid to employ an extra machine, such as a motor grader, where the going was heavy, to keep the haul-roads clear, so as to gain even a fraction of a mile-per-hour in haulage speeds. That was something which plant manufacturers had been saying for years, and to hear it said at a meeting at the Institution was very encouraging.

The Author had stated that one should not believe manufacturers' figures regarding performance. He had said that they were given in all good faith, and Mr Ritchie could confirm that, but it was usually stated at the bottom of the brochure that the figures should not be taken as true on every kind of job. The manufacturers were careful to point out that different kinds of soil and different kinds of operators would give different sets of figures. Mr Ritchie did not know who it was who had said that figures could be made to prove anything, but it was certainly true. Nevertheless, he thought that the Author was a little unfair to manufacturers, and particularly to shovel manufacturers (though Mr Ritchie was not speaking with personal experience there), in saying that their figures were probably based upon ideal time-cycles taken on test grounds under ideal digging conditions. Any reputable manufacturer tried to gather data from as many different jobs as he could, and to collate those data for the benefit of the users, his customers, on whom he must rely for his living.

Lip service was paid to the need for proper maintenance by very many people, including direct-labour employers, contractors, and quarry owners. Mr Ritchie looked at the question from the point of view of a manufacturer of rubber-tired transport. Those people were apt to say "Yes, we have a maintenance system in operation," but often they were deceiving themselves and not getting down to the problem in a big way. They were not prepared to take on a first-class mechanical man with thorough-going

methods—a man who really knew the job—and pay him a proper salary, in order that their machines should be well maintained.

Mr Ritchie's firm had had experience of two iron-ore mines in North Africa, not 30 kilometres apart, where some of their equipment was employed. Those mines employed exactly the same types of machine on exactly similar haulage jobs—muck-shifting, taking the overburden away. It was hard dry going, and dusty. At one of those mines the units were driven by European labour and there was a first-class maintenance workshop to which the machines were brought at regular intervals. Those machines were running to-day (years after being first installed), at an extremely low maintenance cost, and, what was more, they were running regularly. The other mine employed native drivers, paying them a little less, and the result was chaos—machines were off for repair frequently and continually gave trouble.

Many parts of the Paper were written in very general terms, whereas Mr Ritchie would have liked to see some more specific examples given, because, after all, if the manufacturer was to present any convincing figures for the customer he would like some really authentic data on which to work. Mr Ritchie confessed that he was fascinated by the graphs in *Figs 10* to *14*, and would like to know whether each represented one graph for one machine or whether the figures on which it was based had been averaged out from a number of similar machines on similar jobs. If the latter, he must congratulate the manufacturer of the 1½-cubic-yard excavator, but it seemed to him that the builder of the 2-cubic-yard excavator ought to look to his laurels.

Mr R. H. McGibbon asked the Author to enlarge on the statement, under the heading "Application," that from the point of view of cost analysis, earth-moving, compared with other operations which were mentioned, was "often more important owing to the relatively small units of measurements compared with the production of modern equipment." A serious cost analysis on any job should provide serious information on the cost not only of each operation but of each process, and it did not seem probable that the unit adopted for earth-moving was any smaller than that used for the other operations which were mentioned.

Referring to the Author's observations on the human element, Mr McGibbon suggested that the major difficulty lay in the conditions under which the men worked and the seasonal influence on their employment, which, in conditions of reasonably full employment, made it difficult to attract the class of men which one would like to get. It was also true to say that boys contemplating apprenticeship to a trade were influenced by their parents' ideas, and it would be necessary to convince the parents that a career in civil engineering work offered more opportunities for advancement than a career in a workshop, for example. The system which the Author had described as being used in his own organization was probably the best solution, and would be likely to remain so until the

general level of mechanical education was raised by the necessity to possess that mechanical ability in order to get a job.

Under the heading "Constructional Considerations" the Author had suggested that all planning operations should be based upon a 45-minute production hour. That figure was of very great importance, particularly when purely mechanical earth-moving jobs were considered, and if it were used in tendering, its accuracy would virtually decide the financial future of the job. It would be interesting to know what factors had been taken into account in arriving at that figure. Did it allow for idle time on machines which were working only spasmodically or standing by, or did it refer only to the output which could be expected from machines actively engaged on specific operations? If the latter, then, bearing in mind the shift-output curve in *Fig. 7*, on what shift time was it based?

Regarding the Author's remarks under the heading "Mechanical Considerations and Field Maintenance," few would contest his opinion that the selection, purchase, and testing of plant should be undertaken under the guidance of a qualified mechanical engineer, but the operation of the plant was a different matter, and would depend on what the Author meant by "operation." If he meant that the mechanical engineer should direct all the activities of the mechanical plant on contracts, it meant that a firm's plant department would be represented on contracts at the same level as the civil engineer or the agent. It would be interesting to hear other views on the desirability of that. Mr McGibbon felt that even in the field which, it would be agreed, should be the undisputed field of the mechanical engineer, the mechanical engineer should be open-minded enough to allow himself to be influenced by his civil engineering colleagues, who often had their particular preferences for types and varieties of plant for the job.

Would the Author say what costs had been taken into account in arriving at the curves of field maintenance costs, *Figs 10* to *17*? If possible, it would be interesting to know the reason for the steep variation, in the case of the Class II tractor (*Fig. 11*), between 6,000 and 7,000 hours, and of the $\frac{3}{4}$-cubic-yard excavator (*Fig. 12*), between 8,000 and 9,000 hours. If the costs were direct-labour and lubricants only, as would seem probable from the scale of the figures, it was difficult to see why the curves should not be reasonably straight lines.

Mr E. U. Broadbent said that the outstanding feature of the Paper seemed to be that the Author had not merely copied out data and calculations from manufacturers' catalogues or from previous works on the subject, but had presented something which was, on the whole, original and the product of his own extensive practical experience.

Dealing with what the Author had said about the effect of the human element on production, Mr Broadbent suggested that, although those statements were far too often perfectly true, they were not by any means inevitably so.

Had the Author considered the effect on production of pre-targeting? It had been found possible, said Mr Broadbent, on about 70 per cent of the work on a major job, to set targets for the machines, and the result, in conjunction with a satisfactory incentive scheme, had been to keep production steady throughout a shift of 10½ hours, broken by a short meal break. The pre-targeting was simply telling the driver what bonus he would earn if he reached a certain point by the end of the shift, and how much he would gain or lose if he went beyond or failed to reach that point. Great care had to be taken to give full consideration to all factors affecting local production, but, once that had been done and the operators' confidence gained, pre-targeting was an important factor in keeping production steady.

Mr Broadbent's experience had shown that, generally speaking, it had not been found necessary to reduce night-shift targets by more than about 10 per cent compared with day-shift targets. It was true, however, that production did drop more quickly under adverse conditions at night; for instance, when it started to rain, production fell rapidly—the roads became bad and trucks could not see their way about. Under reasonably good conditions, however, certain types of machine, such as draglines and scrapers, lost very little by night compared with their work by day, and even haulage units need not do so if roads were sufficiently wide and tips were open and well lighted.

One point of importance on night-shift work was that it was advisable to stop work in good time if it started to rain, because an hour's work in the rain at night could entail two hours' work sorting out the roads and tips next morning.

The Author had referred on p. 63 to the importance of simplifying an operator's work by careful attention to job lay-out, and Mr Broadbent gave a striking example of what could happen when an operator's work was simplified. It concerned a 2¼-cubic-yard dragline which had been variously used to dump overburden and to load large dump-trucks, and then transferred to load into a large hopper feeding a conveyor. Very soon after the transfer its production went up, and it had maintained an average production 10 per cent higher over a long period, reaching a production, for considerable periods, more than 20 per cent higher than on simple casting or loading dump trucks. The reasons for that appeared to be: first, it was possible to place the hopper to keep the angle of swing very small; secondly, the feed was continuous; thirdly—which he would emphasize—the hopper became the focal point of a working cycle, and the operator, after a very short time, knew the exact position and the height at which to tip, thus saving seconds on every cycle, even compared with casting.

The Author had also referred to the advantages of forward preparation, and Mr Broadbent wished particularly to refer to the use of rooters on hard surfaces. To elaborate the point he cited the case of a job where

there might be need for eight crawler tractors initially. There were several ways in which they could be used; one could use all eight towing scrapers, or seven towing scrapers and one with a rooter or push-loading, or six towing scrapers and one with a rooter and one push-loading; and there were other combinations. As the work progressed, through vegetable soil and subsoil into lower strata, the best combination might change more than once. It was not enough to decide at the start that such-and-such equipment or such-and-such a combination would be used and leave it at that; the engineer had to be prepared to switch his machines at any time to the combination which would give him the best output. At the same time, he should always be on the look-out for chances of doing some extra work cheaply. In a scraper job it might be possible to do some cheap bulldozing, and advantage should be taken of that, even if the cost of the scraper work was thereby raised fractionally.

In dealing with selection of gradient for haul-roads (see p. 79), the Author had said "the steepest gradient at which full tractive effort can be obtained in the lowest gear with the maximum load and under the most adverse weather conditions should be determined; the necessary climb should then be obtained over the shortest possible continuous length of haul-road." Mr Broadbent found that statement somewhat provocative, and made some calculations. A 180-horse-power Euclid dump truck with an all-up weight of 155,000 lb. had a gradability figure of 37 per cent in bottom gear and 19 per cent in second gear. He assumed that the rolling resistance could vary between 2 and 16 per cent adverse-grade-equivalent. The worst condition that would be obtained was about 16 per cent, and that gave a possible gradient of 20 per cent, which the Author had suggested was the correct one to choose. The truck could go up that 20-per-cent gradient, requiring 50 feet to rise 10 feet in 13·6 seconds. If that gradient were reduced to 14 per cent, the average rolling resistance could be taken as 5 per cent—it was usually between 3 and 4, but it could go up to 5—and that meant that in all normal conditions the vehicle could go up that hill in second gear, travelling 71 feet 6 inches but doing it in 9·7 seconds, thus saving 4 seconds on that rise of 10 feet on every trip made under normal conditions. Mr Broadbent was ready to admit that if, on a bad day, the rolling resistance increased above 5 per cent, it would be necessary to go into bottom gear and it would take a little longer; would the Author elaborate on that point? It might be that the importance of suiting the gradient to the machines which were going up it, and planning it to give the best results, was not generally recognized.

Major J. H. Fyson, with regard to the Author's reference to the training of operators, explained the procedure in the British Army to-day, because, he said, many contractors might employ ex-Army personnel who would claim to be operators. Although the Author had said that the machines used in the war showed that very little training in maintenance was given, at the present time training *was* given in maintenance to

operators, and the Army did not employ separate teams to service the machines. A system, taught to all operators, was in force, and consisted in a rigid routine to be observed before getting on the machine and starting up, a timed lubrication scheme based upon hours worked, and finally a mechanical-task system designed to cover the machine in about a fortnight. Of course, if some unusual noise occurred, Army discipline did not insist on waiting until the time for the appropriate task arrived a fortnight later.

On the subject of the qualities which operators should possess, he agreed with the Author that they needed enough knowledge to carry out maintenance, but did not the Author consider that an aptitude for the job, which included good nerves and hardiness, was very much more important, and in fact essential? The high degree of skill reached by a number of Indian Army operators during the war seemed to prove that point.

The Army had recently become fully aware of the importance of the engineers (actually Officers) knowing something about the plant and not being liable to be misled by the operator, and the R.E. Officers they were getting now were, or would be, trained in plant operating, at least very briefly.

Mr G. M. Warren suggested that the Author had been excessively cautious in basing his estimates upon a 45-minute production hour. Mr Warren was under the impression that the 50-minute hour was generally accepted, and would like to have the Author's opinion on that.

It seemed from the Paper that the working of approximately a 12-hour shift was generally accepted, but from *Fig. 7*, which was exceedingly interesting, it would appear that it would be highly beneficial to have an 8-hour shift, and the 7½-hour shift in the U.S.A. to which Mr Caseley had referred was probably based upon similar information to that contained in *Fig. 7*. That Figure also showed that maximum efficiency was obtained over a period of 7 hours, so that with an 8-hour shift, if the men to work it could be obtained, there should, judging by the graph, be an overall efficiency of about 85 per cent.

The Author, in reply to Mr Caseley's question about *Fig. 7*, said that it did apply to a one-man shift. Mr Caseley had also mentioned the three shifts totalling 22½ hours worked in America and had referred to the omission of forward preparation from the Paper. The Author felt that had he incorporated a section on forward preparation he would in effect have been saying that his competitors had no brains and that he must tell them how to do their job. He had always assumed that those who used heavy earth-moving equipment would make use of forward preparation when the occasion arose. Mr Willment was apparently operating 50 feet below the bed of the Thames, and the Author proposed, with Mr Willment's permission, to take an early opportunity to look at that job.

Mr Ritchie had said that the manufacturers of equipment gave

absolutely accurate figures in their manuals. There could be no doubt about that, but those figures related, the Author suggested, to brand new equipment, whereas with equipment which had been in use for a long time it would not be possible to produce some of those figures. No doubt the figures were given in good faith, and his own organization had obtained something approximating to them, when operating new equipment.

Mr Ritchie had referred to maintenance in service and to the 1½-cubic-yard and 2-cubic-yard excavators. In the Paper, the Author had tried to suggest that users were inclined to overload their equipment, and it would probably be found from the maintenance cost of the 1½-cubic-yard machine that it was not expected to stand up to the arduous task to which the 2-cubic-yard machine was subjected. *Figs 10–17* had been prepared after careful study of equipment over a number of years and each of the graphs referred to not less than six units.

In reply to Mr McGibbon, the passage from the Paper which he had quoted related to the low value of the cost of a unit of excavation in relation to a yard of concrete, or something of that nature. It was necessary to carry out a number of operations in heavy earth-moving in order to produce the same money result as would be obtained from 1 cubic yard of concrete, which could be put into the mixer in one operation.

A great deal had been said about the human element. The lack of training schemes was very obvious at the present time. There were not the training schemes to train efficient operators and so reliance had to be placed on the people immediately available. It had been suggested that it was possible to increase production by bonus systems and various other bribes. Certainly that was possible, but when a man had to be bribed to give greater production one might give him half-a-crown and he would cost five shillings in other ways, because if he had to hit a target, which would be assessed at a fairly high figure, something had to suffer. What was really wanted was more intelligent operators in the industry, who should be given permanent employment and better conditions than they would have today.

There was a colossal capital investment in heavy equipment. Some machines cost £100,000, and the cost of excavators worked out at £10,000 to £12,000 per cubic yard of bucket capacity. A man might own a small motor-car and would scarcely let anyone else breathe on it, yet he was willing to hand over a machine costing £25,000 to somebody who might be quite unqualified to handle it.

Fig. 7 represented a 12-hour shift, but it was obvious that that graph, which had been prepared over a number of years, clearly illustrated the advantage of the 8-hour shift. If, however, the construction industry tried to put its men, assuming, that a sufficient number could be obtained, on an 8-hour shift, consideration would have to be given to almost doubling the existing hourly rate of wages. Apart from that, there were not

sufficient operators available to make it possible to run two shifts, let alone three. As time went on that position might change.

Mr McGibbon had referred to the statement under the heading "Application." The small units of measurement referred to in the Paper, compared with the production of modern equipment, simply referred to the fact that the cost of producing one cubic yard of excavation bore no relation whatever to the cost of laying one lineal yard of pipe or producing one cubic yard of concrete.

Mr McGibbon had further dealt with "Mechanical Considerations and Field Maintenance." It was never suggested or intended that a mechanical engineer should direct the activities of mechanical plant on contract sites.

It would not be disputed that where large fleets of mechanical plant were used upon a contract, the presence of a fully qualified mechanical engineer, whose sole responsibility would be the maintenance and care of the plant on the site, would surely add greatly to the production obtained on that contract.

Mr McGibbon would not suggest that field workshops and site organizations should be under the control of a civil engineer who had no mechanical experience other than the actual operation of the contract and the placing of the machines on the right spots.

It was not suggested or implied that the mechanical engineer should in any way influence the civil engineer or agent in the selection or preference for types and varieties of plant for the job. It suggested, however, that the civil engineer should at all times consult with the mechanical engineer as to the dependability and productivity of the equipment which he was selecting.

Regarding field maintenance costs, *Figs 10 to 17* referred to the hourly maintenance costs of each unit—that was to say, labour on repair and spare parts, together with overheads and other administrative costs in the repair of the equipments referred to.

When one had to deal with the repair of equipment, it should not be forgotten that field workshops, head office, or depot workshops and machine shops had to be taken into consideration as part of the overheads appertaining to the organization in question.

The graphs referred to should not be treated as dealing with the repair costs for single units. They referred to average costs of keeping a battery of equipment of the same size in operation.

Mr Broadbent had referred to pre-targeting. In setting targets it was essential to pay special attention to each job, because no two jobs were alike. Everyone tried to set targets for their operators and hoped they would be achieved. It should be borne in mind, however, that excavator operation was a monotonous job. If one sat on the deck of a unit for a week and watched the operation, slinging out a bucket and dragging in a lump of muck, one must admire some of the operators for the way that they

stuck at it. Some of them were so well trained that they could almost do it in their sleep, because they got into a sort of rhythm.

Mr Broadbent had also referred to what was presumably static plant loading into a hopper. Production in that case should go up, because it was a question of operation between two fixed points. In the Author's own organization it had been tried out, and it had paid dividends over and over again. Two bulldozers had pushed the material to the shovel to prevent the shovel wandering about the site; by keeping it static it had been possible to raise production.

Turning to Mr Broadbent's reference to the grades, it would be easy to spend a long time working out figures on that subject. In the Paper, grade resistance had been referred to in a general way, and the Author felt that that was all he could do. If, by referring to grade resistance, rolling resistance, and rim pull, he had aroused curiosity in the minds of owners and operatives he would have done something to draw attention to the fact that those were matters which could be of assistance in getting more economic production out of their machines and lowering costs.

He assured Major Fison that he had no intention of being too critical about the training given in the Army, but he would suggest that a little longer time should be spent on machine operation. He had a great admiration for the way things were being done in the Army, and his reference had been to the war years, when there had been no alternative to what had been done. The Army then had requisitioned the contractor's machines, but not the operators, because it had been thought that the machines were easy to operate. There had been no opportunity to train the boys who were set to work them, and the result had been seen in the purchase of war surplus. He did not think it would be denied that these machines had not been taken care of, but that had been for obvious reasons. He did not suggest that the Army was not giving good training today, and the Army was in a far better position than were contractors to train machine operators, because at least the Army could keep them for a period of time. Contractors would all hope to get back from the Army men who had been properly trained.

The Author agreed that Mr Harding's firm had been responsible for the operation of the first large fleet of tractors and scrapers in Britain.

A good deal had been said about the 45-minute hour. One could make it 50 or 55 minutes, but one would be lucky to get even a 45-minute production-hour today. The average operator today liked a smoke and to get off his machine now and then and to drink tea. He might be allowed 10 minutes for drinking tea, but in fact he drank tea at various hours of the day. The production hours of the Author's company did not give more than a 45-minute hour, and taking the average run of construction work today he believed that one was doing very well to get an average of 45 minutes. One had to bear in mind that rationing was still in operation and that there was such a thing as human fatigue. The operator liked to

take home the largest possible wage-packet and would work 60 to 70 hours if given the opportunity. All those factors taken together had the effect of reducing production to a 45-minute basis. He did not suggest that one should adhere rigidly to 45 minutes; it depended entirely on the job, but over an extended period one was unlikely to do better. If the Author had his way he would not operate heavy earth-moving equipment for more than 40 weeks in the year, but contractors were compelled to plod along in the mud for 50 weeks.

The closing date for Correspondence on the foregoing Paper has now passed without the receipt of any communication. No contributions can now be accepted.—Sec. I.C.E.

PUBLIC HEALTH ENGINEERING DIVISION MEETING

13 January, 1952

Mr G. M. McNaughton, Member, Chairman of the Division, in the Chair

The following Paper was presented for discussion and, on the motion of the Chairman, the thanks of the Division were accorded to the Author.

Public Health Paper No. 5

"The Storage, Collection, and Disposal of Domestic Refuse"

by

Jesse Cooper Dawes, C.B.E., M.I.Mech.E.

SYNOPSIS

The work undertaken by local authorities in collecting and effectively disposing of 10 million tons of domestic refuse each year, at a cost to local rate funds of about £16 million, is examined in detail from the time the refuse is produced until the final disposal.

Storage of refuse at, or near, dwellings, or other premises, to await collection is considered from a sanitary standpoint and approved methods are outlined. Support is given to the modern view that, in the interest of sound sanitation, portable standard receptacles of approved size, design, and construction, should be provided and maintained by local authorities, under powers conferred by the Public Health Act, 1936, as part of their normal collection equipment.

The value of quantitative analyses to record the average composition of domestic refuse, and the importance of recording actual weight yields per 1,000 population, are related to the economics of collection and disposal.

Types and capacities of collection vehicles are referred to and related to local conditions; frequency of collection from dwellings is discussed; and specific principles to be observed in the organization of collection work are suggested.

Special mention is made of the importance of separate collections of organic kitchen waste, and its subsequent conversion by heat treatment into a sterile feeding stuff for pigs and poultry.

Five methods of refuse disposal are discussed in some detail: controlled tipping; separation-incineration; direct incineration; pulverization; composting. Reference is also made to salvage and utilization.

Introduction

It is a remarkable feature of the sanitary history of many if not all countries, including the progressive ones, that the important service of refuse collection and disposal failed to secure adequate consideration even after it had been clearly established that the work was fundamental to the success of any comprehensive scheme of municipal sanitation. There were three reasons for this: (a) cost, (b) the label of meniality, and (c) the fact that it was a service from which no political advantage could be extracted.

The requirements of modern domestic life demand, except perhaps in scattered rural areas, that Local Authorities shall provide out of rate funds, properly balanced and efficient refuse collection and disposal services.

By " balanced services " the Author means that the standard of sanitary and administrative efficiency for both collection and disposal should be equally satisfactory. In some countries elaborate and costly collection services are associated with extremely insanitary disposal arrangements. This is quite illogical and suggests that more consideration has been given to publicity than to public health.

It is sometimes claimed, but less frequently than in former times, that for both the collection and disposal services to be highly efficient would entail excessive expenditure, and that some local authorities cannot afford both. The Author believes that any great disparity between the efficiency of the two services can be very wasteful and his experience has shown that by the use of a sound unit-costing system it is usually possible to provide an efficient all-round, or balanced service at a comparatively reasonable cost.

Domestic refuse possesses definite potentialities for evil. Flies and vermin may collect filth and, possibly the disease organisms which thrive on it and convey them into dwellings, hospitals, dairies, workplaces, shops, and so on; such organisms may also be distributed by winds. Further, there is the ever present risk of nuisance or annoyance.

For these reasons, it is important to keep in mind the fact that whatever the risks may be, they are present during storage, collection, and disposal; there is, therefore, a need for a uniformly high level of all-round efficiency, or correct balance.

The precise annual cost to local rate funds of collecting and disposing of the " dry " domestic refuse produced in England and Wales (amounting to 10 million tons or more) is not at present known, but has been estimated at more than £16 million, the approximate proportion of the costs being: refuse collection 70 per cent; disposal 30 per cent.

For 10 years prior to 1939, local authorities with populations of 20,000, or over, were invited to supply, to the then Ministry of Health, annual statements setting out all the details of their local refuse services, together with specified unit costings, on a uniform basis. The Ministry then compiled, from the data supplied, the " Annual Public Cleansing Cost Return " which was published by H.M. Stationery Office. It was bought freely and, from the valuable information it contained, local authorities became apprised of the aggregate and detailed unit costs for all districts, including those similar to their own. The publication of this Return was discontinued during the war and, so far, it has not been re-introduced, but it is now reported that its re-appearance can be expected in the near future. The last issue published indicated a total collection-and-disposal cost of about £7½ million for 1938.

The approximate population of England is 41,250,000, and of Wales, 2,600,000. In the two countries there are 993 urban, or non-rural, authorities with a total population of 35,500,000.

This Paper is concerned only with the collection and disposal of refuse in urban districts, although the principles, methods, and equipment operating in the more thickly populated rural districts are more or less the same as those of the urban districts.

Direct labour is employed to collect about 95 per cent of urban refuse, and it is customary for local authorities to provide and maintain equipment, including transport units, and to make their own disposal arrangements.

Principles to be Observed in Modern Refuse Storage, Collection, and Disposal Work

The cumulative effect if developments in modern practice in England and Wales, and the requirements recognized as necessary to protect public health, to satisfy the developing aesthetic sense of the population, and to comply with the call for strict economy, have had the effect of establishing certain fixed principles upon which modern collection and disposal methods should be based. These principles are enumerated below.

Storage of Refuse at Self-Contained Dwelling-Houses

(1) Refuse should be stored in portable galvanized steel receptacles of appropriate capacity, of standard design and strength, and provided with close-fitting covers. Such receptacles are sightly and sanitary, and keep the refuse as dry as practicable.

(2) Storage receptacles kept outside dwelling-houses or other premises should be located in positions easily accessible to the occupiers and to the refuse collectors. This matter should receive special attention when new houses are at the design stage.

(3) Storage receptacles kept inside buildings should be emptied daily.

Local authorities have powers under the Public Health Act of 1936 enabling them to provide and maintain domestic refuse receptacles at the cost of local rates, or alternatively, at an annual charge to the owner or occupier which must not exceed 5 shillings. These powers enable a local authority to control the design, capacity, and construction of the receptacles to be used in its district after considering local circumstances and collection arrangements; they also impose a duty on the authority to see that every house is at all times provided with a sound receptacle fitted with a close-fitting cover. British Standards for four sizes of mild-steel refuse receptacles (1, 2, $2\frac{1}{2}$, and $3\frac{1}{4}$ cubic feet) have been issued by the British Standards Institution, on the recommendations of a representative committee of technical experts.

The Author's experience of bin-provision schemes has shown that they

are definitely to the advantage of all concerned, including the refuse collectors. Provision by the local authority as part of its collection service is strongly to be recommended, because it is at the dwelling-house where improperly stored refuse is capable of doing the greatest amount of harm; whilst on the technical side it is helpful to the collection authority to receive the refuse at the final disposal point in as dry a condition as practicable. Unsatisfactory storage at dwelling-houses is always a very weak link in the chain of efficient refuse collection and disposal.

Storage at Blocks of Flats or Large Stores

In London, and some provincial cities, there are multi-storeyed blocks of flats where the refuse is stored in British Standard rectangular or cylindrical dustless portable steel containers of approximately 1¼ cubic yard capacity. These strong containers, which are of special design, are sited at ground level and, generally, the refuse is passed down to them through vertical well-ventilated chutes, of 15- to 18-inch-diameter circular section, usually fixed outside the building. The feed hoppers opening into these chutes are sited in approved positions within the flats and are so constructed as to prevent the escape of dust and smells into the dwelling. The rectangular type of containers are designed to rest on low-chassis carriers for quick removal by the collectors, and from these carriers they are mechanically lifted on to, or unloaded from, motor trucks designed to carry six full containers which are replaced by empty ones at the time of collection. The cylindrical containers are mechanically emptied direct into the collection vehicle. Some local authorities supply removable containers on charge to large stores for the storage of trade refuse pending removal.

The Collection of Refuse

Refuse should be collected regularly at appointed times and without unnecessary delay; when the fixed time of collection is known to the occupier it should not be altered without notice, except in unforeseen circumstances.

The frequency of collection will vary according to the locality and the class of refuse, but the maximum period between collections should be as short as practicable.

All the refuse collected should, whenever possible, be weighed, and when this is impracticable, the weight should be based on the average of one, or more, comparable districts for which actual weight figures are available; it should *not* be estimated or guessed. Sound unit-costing is impossible in the absence of reliable weight figures.

Refuse-Collection Vehicles

The design of vehicles should be considered in relation to the class of district and the type, or types, of refuse-storage receptacles in use; the

vehicle body should be completely enclosed so that its contents are never visible during transit.

They should be capable of being loaded without risk of dust, or other refuse, being scattered, and should be as silent as possible in operation. They should be quick moving, and designed to discharge their contents smoothly and quickly.

The design should not offend the aesthetic sense, and the vehicles should, at all times, present a clean and smart appearance.

Refuse-Disposal

Refuse should be dealt with immediately on arrival at the point of disposal, if possible by a single handling; collected refuse should not be submitted to prolonged exposure.

The disposal process should be such as not to cause nuisance or annoyance from any cause, nor expose residents in the neighbourhood to insect or vermin infestations.

In designing disposal plants reasonable welfare conditions should be provided for the workmen.

Classification of Refuse

There are three classes of domestic refuse :—

Wet refuse.—This includes only faecal matter, and it is not necessary to discuss collection or disposal methods, because the tonnage to be collected is now a negligible quantity; as and when adequate water supplies and sewerage are available, this class of refuse will disappear. In the few districts where small quantities of "wet" refuse have to be dealt with, the method of disposal is on suitable land. Reduction by heat concentration to a useful nitrogenous fertilizer is practicable only when the tonnage justifies substantial expenditure on special plant.

Mixed refuse.—This is a mixture of faecal matter and dry refuse when these two classes are stored in a common receptacle such as an ashpit or privy midden. The same remarks apply to "mixed" refuse as to wet refuse, except with regard to reduction by heat concentration.

Dry refuse.—This is ordinary mixed domestic refuse, devoid of the presence of any faecal matter or free liquid. (Quantitative analysis are given in Tables 1 and 2.) The quantity involved in England and Wales amounts to 10,000,000 tons, or more, each year.

The systematic collection of dry refuse should take place weekly or more frequently, and the distribution of dust should be avoided. The hygienic collection and disposal of such a large annual tonnage of solid matter is a big task, but it is, in general, being done satisfactorily. From a public health standpoint that is a matter of very considerable importance. The composition of "dry" refuse varies within fairly wide limits with the

seasons of the year, except as between spring and autumn when average climatic conditions are more or less comparable. Composition can be strongly influenced by local industry, especially coal mining in districts where coal-allowance schemes are in operation and the allowance coal is unscreened, with the result that the mineral content and, consequently, the tonnage, are greatly increased.

Tables 1 and 2 set out typical average and seasonal, quantitative analyses, based on systematic and uniform methods of sampling in thirty cities and towns before 1939.

If similar tests were made on present-day refuse, the results would probably reveal important changes. In the many towns and cities now operating separate collections of kitchen waste the "vegetable and putrescible" content figure would be much lower, and the mineral content, generally, would be higher in all districts where the domestic coal now supplied results in a higher residual ash. Separate waste-paper collections would also have a marked effect. These are important points when disposal schemes are under consideration.

TABLE 1.—AVERAGE PRE-WAR QUANTITATIVE ANALYSIS OF THE DRY REFUSE OF THIRTY TOWNS AND CITIES, SHOWING THE PERCENTAGE BY WEIGHT OF THE NORMAL CONTENTS.

Contents	Per cent
(a) Fine dust (minus $\frac{5}{16}''$)	36·35
(b) Small cinder (between $\frac{5}{16}''$ and $\frac{3}{4}''$)	14·38
(c) Large cinder (larger than $\frac{3}{4}''$)	6·25
(d) Vegetable and putrescible matter *	13·23
(e) Waste paper	14·29
(f) Metals: 1. metal containers	3·01
2. other metals	0·99
(g) Rags	1·89
(h) Glass: 1. bottles and jars	2·11
2. broken glass	1·25
(i) Bone	0·48
(j) Combustible debris not classified above (wood, straw, leather, etc.)	2·14
(k) Incombustible debris not classified above (bricks, stone, pottery, etc.)	3·63
	100·00
Volume: cubic feet per cwt	6·18
Yield per house per week (lb.)	37·54
Density of refuse:	
Cwt per cubic yard	4·37
Lb. per cubic foot	18·15

* Separate collections of kitchen waste not in operation

TABLE 2.—SEASONAL QUANTITATIVE PRE-WAR ANALYSES, SHOWING THE PERCENTAGE BY WEIGHT OF THE NORMAL CONTENTS OF DOMESTIC REFUSE PRODUCED DURING EACH OF THE FOUR SEASONS OF THE YEAR.

Contents	Autumn	Winter	Spring	Summer
Fine dust (minus $\frac{5}{16}''$)	37·05	42·77	40·11	25·46
Small cinder (between $\frac{5}{16}''$ and $\frac{3}{4}''$)	14·62	18·11	15·23	9·55
Large cinder (larger than $\frac{3}{4}''$)	6·26	7·29	7·07	4·39
Vegetable and putrescible matter *	15·53	7·78	8·35	21·27
Paper	12·86	11·18	13·19	19·93
Metals: (a) food containers	1·82	1·73	2·03	2·92
(b) other containers	0·86	0·71	1·09	0·87
(c) other metals	0·91	0·83	1·00	1·22
Rags	1·73	1·41	1·90	2·52
Bottles and jars	1·87	1·96	2·22	2·41
Cullet	0·96	1·17	1·24	1·60
Bones	0·45	0·41	0·45	0·61
Combustible debris	1·78	1·15	2·32	3·32
Incombustible debris	3·30	3·50	3·80	3·93
Yield per house per week (lb.)	37·97	37·60	40·55	34·54
Density of refuse:				
Cwt per cubic yard	4·32	5·12	4·32	3·74
Lb. per cubic foot	17·92	21·25	17·92	15·50

* Separate collections of kitchen waste not in operation

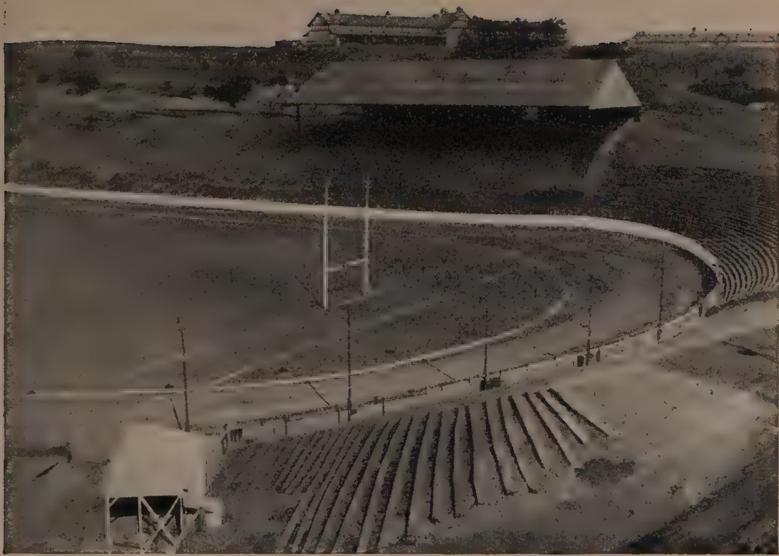
NOTES ON THE YIELD AND COMPOSITION OF DRY REFUSE

Domestic refuse is capable of serious fly infestation, particularly by the housefly (*Musca domestica*), and, as a result of personal observations over a long period, the Author is satisfied that this fly is able to locate house refuse wherever it is exposed. Further, after feeding upon it, this fly, in particular, frequently passes direct to dwelling-houses, dairies, hospitals, shops, and other premises, where it proceeds to feed upon liquid and solid foodstuffs, and to vomit and evacuate faeces. It also has the habit of using suitable foodstuffs, such, for instance, as sugar, to rid its legs and body of the filth which has become attached whilst feeding on refuse.

Given favourable climatic conditions, and the requisite amount of moisture, this fly will breed in dry refuse, but it has been the Author's experience that it does not use well kept and properly designed covered receptacles at dwelling-houses to any serious extent for breeding purposes, provided the collection service is efficient.

Before 1940 it was not the custom in Great Britain to separate domestic refuse at the source. A single receptacle was used to contain all the dry refuse produced at a dwelling. Much mechanical separation work was done at a later stage, as will be explained, but at the time of collection the refuse was mixed together, and this is still the custom except in districts where

Fig. 2



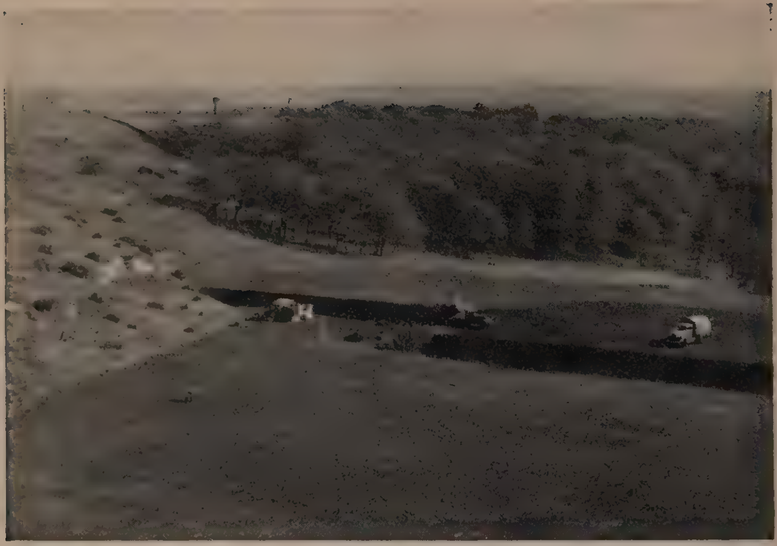
ODSAL STADIUM, BRADFORD (CAPACITY, 100,000). PART OF FOOTBALL FIELD, SPEEDWAY TRACK, AND TERRACED EMBANKMENTS

Quantity of refuse used in construction: 603,000 tons (2,412,000 cubic yards). The building shown above the grandstand is a sanatorium erected before the stadium was commenced.

Fig. 3

FORMATION OF PLAYING PITCH AND SPEEDWAY TRACK

Fig. 4



Extension of Stadium Car Park in Adjoining Odsal Valley

Fig. 5

Bradford Grammar School Sports Fields under Construction

More than 500,000 tons of refuse has been tipped so far. An extensive area to the left of the picture and adjoining the new school buildings has been completed and is now in regular use as playing fields.

Fig. 6

By courtesy of "Croydon Times"]

TOP SOIL EXCAVATED AND PILED ON EACH SIDE OF WIDE TRENCH IN READINESS FOR USE AS FINAL COVER AT CROYDON

Fig. 7

By courtesy of "Croydon Times"]

REFUSE BEING TIPPED INTO TRENCH

Fig. 8

By courtesy of "Croydon Times"]

COVERING MATERIAL BEING SPREAD AND LEVELLED

Fig. 9

TIPPING WORK COMPLETED AND AREA GRASSED

"kitchen waste" is separately stored and collected for subsequent conversion into a sterilized feeding stuff for pigs and poultry.

Very early in the war, local authorities were officially asked to collect kitchen waste separately, and dispose of it to pig and poultry feeders with boiling apparatus to sterilize it in accordance with the terms of a Statutory Order which specifies "exposure to a temperature of boiling (212° F.) for not less than a period of one hour." This Order was made in 1931, by which time it was known that kitchen waste was a carrier of the virus of foot-and-mouth disease brought into the country in imported meat.

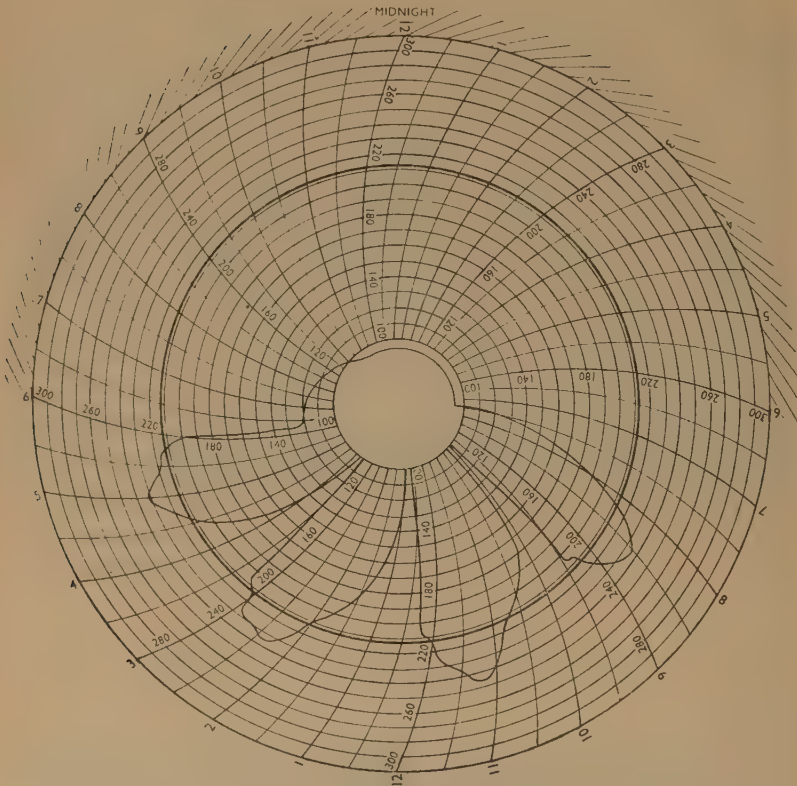
Many costly and wasteful outbreaks of this disease occurred soon after the beginning of the war which the Veterinary experts of the Ministry of Agriculture attributed to the extended use of unsterilized raw kitchen waste as a feeding stuff; at the same time the Ministry reported that it was necessary not only to continue to use it, but urgently to increase supplies. This led to the establishment of sixty-six sterilization stations up and down the country, and local authorities within economic transport distance of these stations were directed separately to collect kitchen waste, and forward their collections to these stations for sterilization and concentration in steam-jacketed cylinders, fitted with electrically driven mixing gear, and operating at temperatures ranging from 212° to 270° F. for a period of one hour. These plants are still operating and more than 200,000 tons of sterile feeding stuff—which is in very keen demand—are produced annually from this class of organic refuse and sold to pig and poultry feeders.

Thermograph charts supply a permanent record of the time and temperature history of the sterilization treatment. A typical chart is shown in *Fig. 1.*

Had it not been necessary to introduce a war-time salvage scheme it is doubtful whether separate collections of kitchen waste, which are made two or three times weekly, would have been introduced, but so long as the strong demand for sterile concentrate continues, it is officially hoped that the local authorities, who own and operate most of the sterilization plants, and private firms, who operate about a fourth of them, will continue to develop this dollar-saving service by increasing the output of concentrate up to the level of demand. To achieve this end, increased collections by the plant-owning and the contributory local authorities will be necessary.

Kitchen waste, when mixed in the refuse is responsible for much of the trouble which arises from inefficient storage, collection, or disposal. In fact, the potentiality of a refuse for causing trouble is in direct ratio to the amount of kitchen waste present; the same material is also mainly responsible for the characteristic odour of refuse and for the risks of nuisance or annoyance. On the credit side, however, it supplies organisms which bring about important changes in refuse disposed of by controlled tipping, or composting, so that there is something substantial to be said in its favour.

Fig. 1



Typical Thermograph Chart

Having regard to the marked variations in composition due to climate, and local causes, it is not possible to set down a standard analysis for dry refuse, but the average and seasonal analyses shown in Tables 1 and 2 are interesting in that a standard sampling formula was used in each of the thirty representative towns and cities, whose total population was about 4 million, selected for the tests, which, incidentally, were continued over several years.

The voluntary practice of making systematic analyses had to be discontinued during the war, and has not yet been re-started, except in a few districts, but when a local authority applies to the Ministry of Housing and Local Government for sanction to raise loans to pay for the erection of new mechanical disposal plant, they may be asked to submit current

seasonal analyses, based on a set-formula, to assist the technical staff of the Ministry to assess the suitability and merits of the proposed plant.

Space does not permit a technical explanation of the information made available by systematic analyses, but its importance and value cannot be too strongly emphasized from the economic as well as from the technical standpoint when collection or disposal problems arise.

Refuse Collection

Yield of Refuse

It is usual to base the unit yield of refuse on the amount produced per 1,000 of the population per day, counting 365 days to the year, and except in special areas, such as mining districts and health resorts, the local yields, when based on actual weighings, vary within more or less narrow limits; the present average yield is probably between 16 and 17 cwt per 1,000 of the population per day.

As already stated it is most important that yield should be based on weighings, and not estimated or arrived at by guessing, because correct weight figures make possible correct unit-cost figures for collection and disposal; from the standpoint of economical administration, correct cost data are essential. It has been the Author's experience that loosely estimated low-cost figures which might appear satisfactory are often seriously wrong and therefore misleading when checked against actual figures for similar areas; sometimes such figures cloak wasteful expenditure and low technical efficiency.

It follows from this that, when local weighing facilities do not exist, unit yield figures should be based on the actual data of one or more similar and comparable districts, in order to supply proof that local expenditure is being kept at a reasonable level. The Annual Public Cleansing Cost Return referred to on p. 99 made this information available.

Frequency of Collection

Generally speaking, dry refuse is collected in urban districts once weekly, but in the central boroughs of London, and in some of the provincial and Welsh districts, a daily service is given; in other special areas a thrice or twice weekly service is provided. Ordinarily, however, it is considered that, given proper storage facilities outside the dwelling-house, by means of portable galvanized receptacles of suitable design and dimensions and fitted with proper covers, a weekly service is sufficient.

As regards the removal of trade refuse arising from the carrying on of a business, a local authority *may* provide a collection service, but a reasonable charge *must* be made for it; it is usual to relate the charge to actual cost. It is estimated that about 700,000 tons of trade refuse are collected and disposed of by local authorities annually and difficulties often arises as to classification. This is because there is no accepted legal definition of

trade refuse, notwithstanding that these difficulties have been occurring over a very long period. Legislation on this point is overdue.

The storage of trade refuse at the source used to be, and in some places, still is, unsatisfactory and the container system, as described above, might usefully be extended where practicable.

Collection Organization

Collection methods, if they are to be efficient, must be organized to suit local conditions. In some districts a single method is possible; in others two or even more may be advisable. The main factors calling for careful consideration are: the "build" or lay-out of a district; the width of streets, especially back streets; traffic conditions; the average "carry," which is the average distance the workmen have to carry refuse to and from waiting vehicles; and average "haul," which is the average distance loaded vehicles must travel from the collection district to the disposal point. A very important factor is the tested cubic yardage of refuse, regularly to be collected and transported; this determines the necessary strength of a collection fleet.

Well designed and well kept collection vehicles are now rightly considered important from the standpoint of environmental sanitation, and for this reason, utilitarianism, pleasing design, sound construction, and smart appearance should be, and in fact, are, combined in the latest types.

Collection and disposal are much more efficient and dependable than in the days of the historic meniality, which by the way, reached up to a few years ago, after putting a blight on the work for centuries. In many cities and towns the workmen, like their vehicles and other equipment, are properly turned out; suitable uniforms and protective clothing, designed and adapted for all conditions and duties, are provided. Much credit for this reform, which is of more practical importance than appears at first sight, must be given to the members of a Special Committee of the Institute of Public Cleansing, who, after much research, drafted standard clothing specifications which are considered by experts to be excellent.

Types of Vehicles

Petrol, heavy oil, and battery-driven vehicles are mainly used on refuse collection work, but it might be of interest to mention that the vehicles used at Croydon, and, possibly, at one or two other places, have been successfully adapted to run on methane gas recovered from sewage. All the above types are designed to stand up well to the heavy wear and tear of house-to-house collection work, and to move as quickly and quietly as practicable. There is no standard type. On the contrary, local authorities have a fine range to choose from according to local circumstances; some prefer side-tipping vehicles with balanced sliding covers, whilst the majority favour the enclosed rear loading and discharge types. Some, as a result of much actual experience, use articulated vehicles, but

whatever type is called for specialist manufacturers are able to supply vehicles of high efficiency.

A brief reference might be made at this point to refuse compression within the collection vehicle. Much experience is available in this, as well as other, countries, on the economics of compressing domestic refuse during collection, but in the Author's view success with this method of handling must depend upon the degree of compressibility of the refuse, and this point should be settled before the system is introduced, in order to avoid the risk of disappointment. In some districts the degree of compressibility might be as high as 40 per cent and in others it might fall below 10 per cent.

The capacities of modern vehicles range from less than 10 up to 25 cubic yards or more, and a decision as to which is the most economically suitable capacity for a district must be decided in the light of local circumstances. The normal pre-war procedure when local authorities sought Government loan sanctions to acquire numbers of new collection vehicles was for them to select several apparently suitable types, and, with the approval of the manufacturers, to organize competitive trials within their districts to demonstrate suitability, observe performance, and record " all-in " unit costs. This procedure may not be practicable now, but in the Author's experience it was thoroughly justified by the results, which were often surprising; the higher priced vehicles not infrequently returned the lowest " all-in " unit collection costs. Incidentally this form of competition had a marked effect on the development of vehicle design which benefited both the Local Authorities and the manufacturers.

Cost of Collection

The average " all in " unit cost of refuse collection, based on the last Annual Cleansing Cost Return for 1938 was 8*s*. 9*d*. per ton, but since that figure was recorded wages have increased by more than 100 per cent, whilst the cost of equipment has increased at an even greater rate with the result that the average cost is now more than twice as much. Before the war the weight of dry refuse collected per man employed per week averaged about 8 tons; now, the figure is lower as a result of a reduction in working hours from 48 to 44.

Methods of Refuse Disposal

The following are the three main methods used to dispose of more than 90 per cent of the dry refuse collected in England and Wales :—

(1) Controlled tipping.
(2) Incineration-separation.
(3) Direct incineration.

Among other methods used to dispose of the remainder are :—

(4) Pulverization.

(5) Composting.

These five methods are separately, but briefly, referred to later. The bad practice of disposal into off-shore tidal waters has, fortunately, been superseded by controlled tipping or separation-incineraton in all save one of the coastal districts where it was formerly operated. A comparatively small tonnage is disposed of, mostly in rural or thinly populated areas, by crude dumping, which is the negation of method. Thirty years ago, 60 per cent of the refuse collected was so disposed of. Now, the proportion is less than 5 per cent. This remarkable change-over represents one of the outstanding features of modern sanitary progress.

Controlled Tipping

The disposal of dry refuse on land by ordered deposition, and by the use and control of the process of natural fermentation brought about by the thermogenic organisms present in the putrescible content, was initiated in England in 1912 after a series of experiments extending over several years. A few local authorities used the method during the first world war, when some remarkable results were recorded at Bradford. The widely known " Suggested Tipping Precautions " of the Ministry of Housing and Local Government (see Appendix) setting out standard control requirements were first issued by the Ministry of Health in 1922, and are now observed in numerous countries. In between the two world wars successful results were reported from hundreds of towns and cities. Incidentally, more than 900 deputations, representing British and foreign local authorities have inspected the Bradford controlled tips, which are internationally known for their excellence.

The Annual Cleansing Cost Return for 1927–28 indicated that 1,696,991 tons of dry refuse were disposed of by controlled tipping in that year ; by 1931–32 the figure had increased to 2,961,976 tons, whilst the Return for 1937–38 gave a figure of more than 5 million tons.

The underlying principles of this method require dry refuse to be deposited in shallow layers, not more than 6 feet in thickness, and covered within 24 hours with soil or other suitable non-combustible material which will form an effective seal. The whole of the refuse can be put into the tip, but it must be tightly packed ; there must be no cavities. The front, or tipping " face " must be kept as narrow as practicable to facilitate daily covering.

To secure effective control of the tip " face " and to restrict the exposure of raw refuse, tips are sometimes formed in strips or sections, the number and width of which do not matter provided that each strip or section is covered on all sides as the tipping proceeds. These strips, or sections, of course, become soil-lined cells in which the biological changes proceed independently. Incidentally, fire does not occur in the cells when

the control is really good, but there have been occasions when unauthorized persons have uncovered the refuse after "sealing" has been completed, and set fire to it. When this happens cell formation localizes the outbreak and makes suppression simple, whereas fire in an uncontrolled refuse tip is exceedingly difficult to fight, and often proves to be a very costly business, as well as a nuisance.

Strip or section formation is not always practicable, and a longer face has to be used. When this occurs there is often a strong temptation to make it too long.

The area of a face, or other exposed surface of raw refuse, should never be greater than that which can be effectively covered or sealed by the end of the day's operations.

"Mound" tips, or tips carried well above adjoining ground level are not permissible under the official precautions. It is usual to select low lying land, deep depressions, disused dry sand pits or quarries and bring up the level by layer-formation to that of the surrounding land. The rate and progress of settlement depends upon the packing and, to some extent, the character of the refuse; uniformity of settlement should follow uniformity of packing—a point of some importance when playing fields or recreation grounds are being made. In Great Britain the rate of settlement varies from about 1 in 8 to 1 in 6. Land from which underground water is drawn for domestic use should not be used for controlled tipping, and it is not permissible under the official precautions to tip raw refuse into water.

Temperature is a natural result of the biological changes which take place in the putrescible content, and the rate of change is in inverse ratio to the air supply into the packed refuse. The more perfect the seal, or cover, the more rapid the rate of fermentation and the higher the temperature, which, of course means the more rapid disappearance of the putrescible matter. Normally, when average dry refuse is tipped under control, a temperature of about 140° F. is recorded at a depth of 3 feet for 10 to 30 days, but 180° F. has been recorded. (When kitchen waste is separately collected, tip temperates are reduced.) After 2 or 3 weeks the temperature begins to fall and continues to do so until atmospheric temperature is reached, when the refuse is dead and the finer grades of it, can, if required be subsequently removed and used, after screening, to cover or seal fresh deposits of refuse. In this sense, dry refuse can be said to contain within itself the elements essential to its own effective disposal, given the necessary conditions. Usually, a period up to 2 years, or even more, elapses before ordinary domestic refuse becomes dead—much depends upon the effectiveness of the seal or cover—but this is of small importance since the refuse, as a rule, is permanently deposited or can remain on site until dead.

When the seal is prompt and good, and air-exclusion precautions are strictly observed, the normal risk of combustion is removed, and where there is no combustion there can be no offensive burning smell or smoke.

Flies do not feed on a sealed cover of soil or dead refuse, so that, given proper covering, the fly menace is obviated. Furthermore, complete covering, associated with tight packing and, particularly, an absence of cavities, has been proved to be a successful anti-rat measure. Another very important point is that a properly controlled tip is not unsightly during the process of formation.

In addition to its sanitary merits as a method of disposal, controlled tipping possesses important advantages. The average cost is comparatively low, unless secondary transport is necessary, and, by proper exploitation, low-lying or derelict land can be reclaimed and brought into use for recreation grounds, or for agricultural or industrial purposes, provided every detail of the "Suggested Precautions" is complied with; to ensure this competent technical direction and supervision are essential.

Controlled tipping, well done, is a sensible method of effective refuse disposal, whether carried out by manual labour or mechanically. *Figs 2* to *5* (between pp. 104 and 105) show normal examples of the manual labour method of formation at Bradford and *Figs 6* to *9* (*loc. cit.*) illustrate mechanized tipping at Croydon.

Separation-Incineration

When suitable land is not economically available for controlled tipping, the separation-incineration method should be the first mechanical method to receive technical examination in the light of the local refuse analyses, site or sites available for plant, and general local conditions.*

More than 90 per cent of the mechanical disposal plants built in Great Britain during the past 25 years have been of this type which, briefly, provides for the preliminary separation of the fine mineral dust (minus $\frac{5}{16}$ or $\frac{3}{8}$ inch) by means of rotary screens and the subsequent incineration of the dustless surplus, or "tailings," following the extraction of any usable materials saleable to industry or agriculture.

Table 1 shows that the mineral dust or fine ash content of a local refuse (minus $\frac{5}{16}$ inch) may be as high as 40 per cent by weight in winter. This dust can be very troublesome if left in the refuse. In the first place it often carries a heavy moisture content which, from an incineration standpoint, is a disadvantage; and secondly, it sometimes has a very low calorific value and more than 50 per cent of it, by weight, might be inert matter. Its effect in a furnace is to keep down the temperature and reduce the value of the clinker. There is always a risk of some of it finding its way in a finely divided state into the chimney to be finally distributed round about—not always within the immediate surroundings of the works.

Several references have been made to the putrescible content; it is ubiquitous. Its presence in the refuse, particularly in the summer months,

* A strong local demand for continuous supplies of pulverized refuse or refuse-compost might modify this view, but experience has so far shown that such a demand is improbable.

when its percentage increases as that of the dust and cinder contents decrease makes it necessary to secure the highest temperatures obtainable in order effectively to oxidize the noxious gases as completely as possible, and avoid the risk of emission of burning odours from the chimney.

By the preliminary extraction of the dust, by screening, the best use can be made of the cinder content; the risk of dust distribution from the chimney is reduced to the minimum, and the production of burning odours is lessened. Furthermore, it follows that the higher the temperature, the harder the clinker which, by the way, is produced by the separation-incineration method at the rate of 22 to 25 per cent of the original tonnage, instead of the usual 33 to 40 per cent by direct incineration. Unfortunately, the economic disposal of clinker, especially of low grade stuff, is now a problem in many districts.

The extracted dust is separately disposed of in several ways. Sometimes it is sold, or given away, at works, for use in heavy land where it has a useful physical effect; or it may be used for levelling up playing fields and recreation grounds; often, however, it is tipped—without nuisance. There is, of course, some biological action when this material is tipped or stored in thick layers and, usually, it is better not to disturb it, unless required for agricultural or other special purposes, for several months, or until it is dead, when, if required, it can be effectively utilized on controlled tips to cover new refuse. Incidentally, comparatively small quantities of this dust have been used for centuries past, after admixture with the special clay, in the manufacture of the well-known London stock brick but, unfortunately, it is of no use in the manufacture of other bricks.

Claims have been made, and supported by facts, to the effect that, after a period of exposure, the surfaces of dumps of this dust have produced good grass, and other crops, without the addition of soil. When Dr Samuel Morris, now of Israel, was at the Hannah Dairy Research Institute, in Scotland, he did some promising research into the fertilizing value of this dust on grass land. He also arranged for Table 3, which shows the trace elements present in the dust, to be prepared at the Macaulay Institute at Aberdeen.

Dr Morris, and others, have stressed the importance of some of these trace elements to the agriculturalist, and one scientist has written that "screened refuse dust is about the only fertilizer in use today which supplies all the elements in one dressing"; in spite of these testimonies, however, the demand for screened dust is negligible.

The separation-incineration process can be designed to meet many salvage requirements. In some districts cinder is mechanically recovered and sold to manufacturers and horticulturists for direct steam-raising or heating purposes, and small quantities are used for burning stock bricks; wastepaper, non-ferrous metals, bones, etc., are easily recovered from the conveyors working between the rotary screens and the furnaces. Ferrous metals are recovered magnetically and mechanically baled.

TABLE 3.—TRACE ELEMENTS

SPECTROGRAPHIC EXAMINATION OF SAMPLE OF SCREENED REFUSE DUST FROM AYR REFUSE-DISPOSAL PLANT

Present in quantity	Present in small quantity	Present in large trace	Present in trace	Present in slight trace	Not observed
Si Silicon	Mn Manganese	B Boron	Ge Germanium	As Arsenic	Cd Cadmium
Al Aluminium	V Vanadium	Pb Lead	Sn Tin	Rb Rubidium	Hg Mercury
Fe Iron	K Potassium	Cu Copper	Mo Molybdenum	Cs Caesium	Au Gold
C Carbon		Zr Zirconium	Ag Silver	Zn Zinc	Y Ytterbium
P Phosphorus		Be Berryllium	Cr Chromium		Sb Antimony
Ti Titanium		Co Cobalt	Ga Gallium		Bi Bismuth
Ca Calcium		Ni Nickel			In Indium
Mg Magnesium		Ba Barium			Tl Thallium
Na Sodium		Sr Strontium			Sc Scandium
		Li Lithium			

This type of plant is more extensive, and more complicated, than that used for direct incineration, because in the latest installations the whole of the operations from the unloading of the refuse to the clinkering furnaces are mechanized ; the furnace accommodation, however, for a given tonnage is practically halved as compared with direct incineration, and the temperatures are substantially higher. Generally speaking, a well-designed separation plant intensively managed, is cheaper in operation than a direct incineration plant. The tonnage dealt with by this method in the seventy plants in the larger urban districts is approximately 2 million tons per annum.

Direct Incineration

Formerly, this method, which is well known, was popularly described as "destruction" and the plants were called "refuse destructors," but these terms were misnomers since matter is indestructible. The early forecasts of abundant supplies of cheap steam and cheap electricity from direct incineration were not fulfilled. Very few plants in Great Britain are now designed to operate on the direct incineration principle, although it is possible to visualize refuse analyses which might justify the method.

Usually, in the more simple types, the refuse is received into a hopper and fed direct to the furnaces from the top ; clinkering is done from the front. Some local authorities using the direct incineration method have difficulty in disposing of the clinker except at a substantial cost, largely because it is "soft," has a heavy dust content, and contains too much metal.

It is not necessary again to refer to the necessity of securing the highest possible temperatures, or to the risks of burning odours and the distribution of dust and grit.

About 1·5 million tons of dry refuse are disposed of annually in England and Wales by the direct incineration method at works which, for the most part, are old.

Pulverization

Under this method the whole of the refuse, as collected, minus such materials as metals, bottles, boxes, etc., which are first removed, is hand-fed into top-feed steel-encased pulverizers, or crushers, of special design.

The pulverizing is done by swinging hammers of alloy steel, specially made to withstand the heavy wear, connected to a main shaft running at 1,000 r.p.m. The hammers continuously strike the refuse as it passes through the machine with considerable force, and dash it against a steel breaking block, after which the mixture falls on to a grinding plate where it is reduced to a requisite fineness for discharge through a screen grid outlet which forms the base of the machine. The refuse receives 4,000 hammer-strokes per minute from an aggregate weight of 70 tons.

Given good management pulverization is a satisfactory process, but, if it is to be economically successful, it is very important that a continuous outlet for the end product, at a reasonable, but satisfactory price, is first assured; experience so far, in England, has shown that the product from average refuse has not met with the demand anticipated.

The domestic refuse collected in The Hague, Groningen, and Zandvoort, is railed to the distant province of Drente where it is stored for several months in large concrete hoppers to undergo partial or complete fermentation. Later it is screened and the screenings are pulverized, and the regular demand for this mixture by agriculturists is twice the supply. This plant has been in operation about 20 years, and the Author has heard expert local users speak in the highest terms of the end product. They assert that it is a good humus former, and a stimulant to microbal life which gives to their soil a better structure and increases its water-holding capacity, with the result that soil erosion is prevented or reduced. The interesting point about all this is that analyses of the refuse pulverized at Drente show that it is comparable with average English refuse! Technical opinion differs as to whether a period of pre-fermentation adds substantially to the agricultural value of this Dutch product. At another, and smaller, plant erected in 1951 at Schiedam, the refuse is first pulverized, and afterwards stored and left to ferment for 6 weeks. Both plants are operated by the same semi-government organization and others are projected.

In countries where wood is the normal domestic fuel, the resultant wood ash gives to pulverized refuse an added value, and might make continuous disposal economically practicable.

Pulverization is not a costly method of treatment but becomes both costly, and very embarrassing, when the product cannot be disposed of as produced. During the past 30 years nearly twenty pulverization plants have been operated in Britain and, with a single exception, closed down through lack of promised demand for the end product at reasonable prices based on production.

Composting

Much has been said, and written, about composting domestic refuse and different values have been placed on the resultant product. Unfortunately, this term is given different meanings in different countries and sometimes in the same country. In Holland the pulverized refuse produced at Drente is described as a complete compost, but in Britain the term is normally applied to a mixture of two or more fermentable substances, for example, sewage sludge and domestic refuse.

If, as a result of natural or slow fermentation, refuse is changed into a useful compost, then the enormous quantities of dead refuse in sealed controlled tips should have some value as a soil improver, but the fact remains that there is practically no demand for it. The current reason for this might be, to some extent, an economic one, but in pre-war days

when agricultural labour was comparatively cheap and this fermented refuse was offered free, or at very low prices, there was little or no demand for it, notwithstanding that many knowledgeable persons strongly recommended its use as a humus former and soil improver.

A Committee of experts was set up during the war by the Agricultural Research Council to study the question of mixing sewage sludge and town (dry) refuse to make a worth-while compost, and a series of field scale experiments was planned and carried through. Finally, the Ministry of Agriculture issued a Technical Communication (No. 7) entitled "The Agricultural Use of Sewage Sludge and Sludge Composts," in which it is stated under the heading "Composts from Sludge and Town Refuse," that "experiments have shown that composting sewage sludge and pulverized town refuse can produce a good manure."

No information is available as to the annual tonnage of refuse now used in Britain for "composting" with sewage sludge, but it must be quite small and it would be to the advantage of all concerned if the figure could be increased since there is much land which might benefit by the adequate use of a compost of this nature.

Another way of producing a refuse compost, is the "rapid," or "induced fermentation," method which is used in some of the districts of Southern France and Italy, and has been tried out by private enterprise in London. There are several systems, but each depends for success on the continuous disposal of the end product at an economic price, as is the case with pulverization. Given a refuse with a high mineral and a low fermentable content, such as is produced in Britain, a costly rapid fermentation system could hardly be expected to succeed. In the London trial referred to, the end product did not command an economic price for agricultural use and, after a prolonged trial the plant was closed down.

Refuse Utilization or "Salvage"

Table 4 summarizes the results of the intensive salvage operations carried on by local authorities in England, Scotland, and Wales between October 1939 and July 1947 to facilitate the recovery of utilizable dry refuse contents. In addition, much useless land was reclaimed and many acres were improved by tipping, under control, much of the refuse remaining after completion of salvage operations. In view of these results, and having regard to the great experience of this work now available, the Author would suggest that, which ever method of disposal is found most suitable for a given set of local conditions, a dominant principle of disposal operations should, in all cases, be maximum utilization within sanitary and economic limits. In other words local authorities should, whenever it is economical and practicable so to do, make available to industry and agriculture such recoverable materials as either, or both, may require for their use.

TABLE 4.—TONNAGE OF WASTE MATERIALS SOLD BY LOCAL AUTHORITIES BETWEEN OCTOBER 1939 AND JULY 1947, WITH INCOME THEREFROM.

Materials	Tons	Income received
Waste paper . . . . (Newspaper, cardboard, old books, etc.)	2,141,779	£ 12,045,210
Scrap metals		
Ferrous metals.	1,585,921	„ 3,188,121
Non-ferrous metals	48,934	„ 1,126,122
Textiles . . . . (Rags — woollen and cotton — sacking, string, etc.)	136,193	„ 1,628,506
Bones . . . . (Household bones only) . .	68,695	„ 285,649
Domestic "Kitchen Waste" . .	2,368,485	„ 5,613,869
Miscellaneous . . . . (Fuel cinder, glass, etc.)	2,546,005	„ 2,359,926
Grand totals	8,896,012	£ 26,247,403

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In conclusion, the Author tenders thanks to Mr C. E. Boast, O.B.E., M.C., M.I.C.E., Borough Engineer and Surveyor, Croydon, and to Mr J. W. Call, Director of Public Cleansing, Bradford, for lending the photographs which have been used to illustrate the Paper.

The Paper is accompanied by eight photographs and one copy of a typical thermograph chart, from which the half-tone page plates and the Figure in the text have been prepared, and by the following Appendix.

APPENDIX

REFUSE TIPS

SUGGESTED PRECAUTIONS

Every person who forms a deposit of filth, dust, ashes or rubbish of a nature likely to give rise to a nuisance must, in addition to the observance of any other requirements which are applicable, comply with the following rules :

(1) The deposit to be made in layers.

(2) No layer to exceed (†) feet in depth.

(3) Each layer to be covered, on all surfaces exposed to the air, with at least nine inches of earth or other suitable substance ; provided that during the formation of any layer not more than (*) square yards must be left uncovered at any one time.

(4) No refuse to be left uncovered for more than 24 hours from the time of deposit; (‡)

(5) Sufficient screens or other suitable apparatus to be provided, where necessary, to prevent paper or other debris from being blown by the wind away from the place of deposit.

(6) No refuse to be deposited in water.

(7) All reasonable precautions to be taken to prevent the outbreak of fires and the breeding of flies and vermin in the deposit. Hollow receptacles likely to provide breeding places for vermin to be flattened or filled before being covered by refuse.

(8) Deposits consisting entirely or mainly of fish, animal or other organic refuse must be covered forthwith with earth or other equally suitable substance to a depth of at least two feet.

(9) Deposits must be maintained in a tidy condition; tins, hollow vessels and other loose debris must not be left lying on or about the place of deposit.

(10) Sufficient and competent labour must be provided in connexion with the deposit to enable the necessary measures to be taken for the prevention of nuisance.

(11) So far as practicable each layer of refuse which has been laid and covered with soil must be allowed to settle before the next layer is added.

(12) Whenever practicable the person making the deposit must avoid raising the surface of the tip above the general level of the adjoining ground.

(13) All refuse must be disposed of with such despatch and be so protected during transit as to avoid risk of nuisance.

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† Unless the circumstances are very exceptional, the depth of the layer should not exceed six feet.

* Appropriate figures should be inserted here after full consideration of local conditions.

‡ The object of this is to provide that even the surface which is allowed to remain exposed under (3) shall be covered up promptly: this should be done within 24 hours. Normally, this figure should not exceed two square yards for every 4 cubic yards of refuse deposited each day to a depth of six feet.

Discussion

The Chairman said that the Author's name was very well known to all those engaged in the field of Public Health engineering, not only in Britain but throughout the world.

Mr C. E. Boast said that his authority, which looked after the interests of about 250,000 people in Croydon, had run the whole gamut of methods of refuse disposal, including one or two to which the Author had not referred and, after rather bitter experiences of pulverizing and composting, had finally made a very definite choice in favour of controlled tipping. There were certain difficulties, because there were usually not many places in a large town where refuse could be tipped. In outside districts all sorts of difficulties might be encountered, such as the powers of the 1947 Town and Country Planning Act, which made tipping "development." Incidentally, it was also rateable because it was considered beneficial occupation of land.

Many authorities who proceeded by that method had to go outside their boundaries and they needed help from the appropriate Ministries in trying to overcome the many difficulties which had arisen since the war.

The method of controlled tipping in Croydon had been brought to a highly mechanized stage. From a pool of mechanical excavating machinery, could be drawn the appropriate equipment for any job. As soon as the excavation was completed, a bulldozer of suitable size was then used. At the moment, a single-cylinder diesel bulldozer manufactured in Great Britain, was proving extremely successful in place of a four-cylinder imported type which cost twice as much and was now almost unobtainable.

After levelling the refuse by this bulldozer, ashes made available by the British Electricity Authority were used for intermediate covering and also for sealing off at the end of the day's work. The ashes prevented rat nuisance. Before depositing the ashes, the surface of the tipped material was sprayed with "gammexane" by means of a mechanical blower. Treatment by hand could not properly be controlled. The machine did an efficient job and eliminated almost all flies, crickets, and leatherjackets.

Mr Boast said that provided a bulldozer was held in reserve in case of breakdown, one operating bulldozer could deal with 1,500 tons of refuse in a 5-day week. The only people then required on the job were a foreman, who had to be a strong-minded individual, and two men whose job it was to move the screens in order to prevent paper blowing away, and to deal with the mechanical blower, and other jobs.

The vehicles were run on methane (produced at the sewage works) in lieu of petrol, and that saved £6,000 a year. Mr Boast hoped that some of his colleagues would refer to their experiences of tipping into wet pits.

Mr Boast showed some lantern-slides illustrating various aspects of the service as operated in Croydon and some of the methane-operated vehicles and equipment in use there.

Mr R. K. MacDowall said that he was concerned with the production of feeding stuffs from the organic fraction of the refuse—the fraction popularly known as the "waste food fraction." Although it was only a minor constituent—approximately one-tenth to one-fifth of the total—it was quite clearly the dangerous element from the public health point of view. It had been stated that without it a refuse would become more or less inert—a stable and neutral material which would cause little difficulty, or certainly less difficulty, in its disposal. Since the waste food fraction was acid in character and high in water content, its removal might prolong the life of the expensive machinery and equipment used in refuse disposal. The Author's views on that point would be of interest to local authorities and to others.

Although the waste food fraction was the lesser constituent of refuse, it would be seen from the Paper that approximately 10 million tons of refuse was disposed of each year, which meant, in round figures, that there were

a million tons of organic matter available. It had been calculated that one ton of waste food matter was, in terms of livestock, roughly equivalent to one bacon pig, so that potentially in the refuse of Great Britain there were sufficient feeding stuffs to rear one million bacon pigs every year.

Mr MacDowall's 12 years of experience had led him to believe that it was impossible to recover that amount completely, and at present local authorities were recovering about 35 per cent of the total, which meant that some local authorities were doing very much better and were recovering perhaps 90 per cent of the theoretical maximum.

Since the war, an important development had taken place in the method of collection. More than a hundred local authorities now supplied individual containers to separate domestic premises, and the results of that apparently simple departure were astonishing. The raw material obtained was rich in bread and low in foreign matter, and was produced abundantly. Roughly, each thousand containers yielded about 150 tons of raw waste in a year. In one city alone, more than 100,000 of these containers would be in use by the end of 1953.

Mr MacDowall pointed out that there was nothing new in using the pig to convert waste products into meat. But the practice of swill feeding had always been recognized as subject to risk. There was not merely the ordinary commercial risk of buying a watery or low-grade feed, but the grave risk of spreading animal disease by taking unsterilized swill to premises where stock was kept. The veterinary officers of the Ministry of Agriculture had proved that numerous outbreaks of foot-and-mouth disease could be traced directly to that cause. Since the scheme started in 1940, roughly 2,500,000 tons of this waste had been sold in the processed condition—processed centrally, away from the livestock; and in no case had it led to any transmission of animal disease. In passing, Mr MacDowall said, it was of interest to reflect that in 1952 the amount of compensation paid to farmers for foot-and-mouth disease was about £2,500,000.

The central processing of the material, which had been one of his personal interests, was a fascinating subject which had led to some interesting problems. When one small site was accommodating some hundreds of tons of this stale material, which in its raw state was rather offensive, the problems were apparent. The material was given a semi-drying process, which was simple, cheap, and effective. It reduced the volume by about two-thirds and the weight by about a quarter, and the product could easily be despatched into the countryside.

In some cases a more elaborate treatment had been given; the material had been dried and ground to a mealy condition, but that had proved expensive and appeared unlikely to be adopted. In other cases, before the heat or drying treatment, the material was given a process of size reduction, generally by pulverization in a swing-hammer type of mill. It then made a more homogeneous product and evaporation was facilitated by the increase of the surface area.

When the National Waste Food scheme commenced during the war, the first processing plant was installed on the initiative of the Tottenham Council. An uphill battle had to be fought to introduce the new feed to farmers. It looked like no conventional material; it was new and strange. But the present position was that there were about seventy processing plants making it, and they could probably sell three or four times what they made. In fact, they had a difficult problem in keeping their customers satisfied.

An analysis of the treated waste might be of interest, Mr MacDowall said. In round figures, it contained two-thirds water, one-third of dry matter; about 5·2 per cent of protein, 3·5 per cent of ash, 2·4 per cent of fibre, 3·1 per cent of fat; and the balance was what the chemist called carbohydrate. Of the dry matter, protein was therefore about 17 per cent, which was an extremely good figure and rather surprising in the present days of meat shortage. In about twelve towns it had been possible also to recover additional waste materials rich in protein. They came mainly from industrial and commercial sources and were often of a very putrescible character. If they were not disposed of quickly they gave rise to a serious nuisance. But when they were introduced into the food they enhanced its value, and a special price structure had been in operation to foster that development.

The production of animal food in the manner just described was developing into a miniature industry. About 1,000 tons a day of waste material flowed into it—and, broadly speaking, every ton produced one pig. In a recent letter, the Minister of Agriculture had thanked local authorities for their magnificent efforts and had indicated that a stable demand for the product was likely to exist for many years. Indeed, he proposed to introduce legislation to regularize the arrangement and give it some permanent form.

Mr John Dossor observed that in the next few years there were prospects of very great changes, not only in the recovery of the organic material mentioned but also in the general system of refuse collection consequent upon district heating schemes and so on. He could not understand why, in some urban and rural areas, domestic incineration in the houses had not become popular. It would appear that the dangerous organic material could be destroyed in the house by means of electric incinerators, at very low cost.

Mr Dossor showed some lantern slides illustrating one of the factories for the production of the organic concentrate, and indicating the advantage of pulverizing the material before it was treated. The factory had been built by private enterprise since the war and had been in operation for about 3 years. It was a small plant, capable of handling about 100 tons a week.

The raw material, after sorting, was fed in at a high level, went through a hammer-mill pulverizer and was dropped into a container through a

valve which was pneumatically operated. The container filled in about 20 minutes or half an hour and the valve closed. The material was discharged from the tank by the admission of compressed air, which forced it through a pipe into either of the steam-jacketed concentrators. Apart from increased cleanliness as compared with belt conveyors the chief advantage of the system was that the pulverizing process, which took some time, could go on concurrently with the cooking process. The discharge of a 2-ton batch of the material into the concentrator took less than 10 minutes. That enabled a greater throughput to be handled by the same size of plant.

Any material which did not require pulverizing and which could be sufficiently broken down by the cooking process alone could be fed directly into the concentrators.

On the sterile side of the factory, the concentrate was taken straight from the concentrating machines and dispatched via a weighbridge. On night shift, however, the material could be left in the concentrator for a longer time and reduced to such a condition that it could be ground into a meal; a small grinding machine was available for this purpose.

Mr James Sumner said that the aspect of public cleansing services which seemed to get most attention was that of refuse disposal, but he would confine his remarks to refuse collection.

All aspects of a cleansing service were essential to its efficiency, for they were all links in the chain. It cost twice as much to collect the refuse as it did to dispose of it, and it could be deduced from the figures in the Paper that an overall saving of one shilling a ton in the cost of collection would save the ratepayers of England and Wales £500,000 a year. Refuse collection, therefore, merited close attention.

Many factors affected the organization of an efficient refuse collection service, not least of which was the type of vehicle to be used. There were several thousand collection vehicles in the country, travelling millions of miles a year, and the type of vehicle merited serious consideration. Mr Sumner supported the Author in emphasizing the relation between the type of vehicle and local conditions. There was no standard vehicle. Many designs had been produced, some of which would suit certain areas, but wherever possible, practical tests should be arranged in the area.

Apart from sound construction, Mr Sumner thought the fundamentals of design would be a low loading line, hygienic loading conditions, and sufficient capacity, consistent with other factors, to reduce the length of haul to the minimum, but there was plenty of room for choice within those fundamentals. It was not sufficient merely to view the various vehicles before making a choice for an area.

On compression devices, Mr Sumner said many different forms were available, but, before deciding on vehicles with compression devices, it was essential to have regard to the type of refuse to be collected. In one local authority with which he had been connected, it had been found that

compression devices would increase the pay load of the vehicle by 40 per cent, but that was not always the case and there must be areas where such devices were more or less useless from the compression point of view. They might provide means of loading the vehicle, but if the refuse was very dense there would be a big strain on the device and the cost of maintenance would make it probably not worth while.

Mr Harold Gurney said that the Author had referred in the last paragraph of the Paper to the efforts made during the war and immediate post-war period by local authorities in utilizing refuse. Although the effort was not inconsiderable, it should be related to the total amount of refuse which local authorities dealt with during that period. The figures given in the Paper showed that during those years about 9 million tons of refuse were utilized for very good purposes, to a value of about £26 million, but the total quantity of refuse dealt with by local authorities during that period was in the neighbourhood of 60 million tons. Thus, utilization as a complete method of disposal was unlikely to be available for all parts of the country.

Mr Gurney said that the town he represented, in common with other centres, were fortunate in having means of disposing of their products. During the past year in Tottenham they had dealt with about 46,000 tons of domestic refuse, and from that they had been able to recover 9,000 tons of fine ash and cinder (minus $\frac{3}{8}$ inch) and 3,000 tons of larger cinder. The fine ash and small cinder was used by brickmakers as an aggregate for the manufacture of stock bricks, and the 3,000 tons of larger cinder was used by the same brickmakers for burning the bricks. A very convenient method of extracting the material from the refuse was in use—a very cheap and simple method—and there was an outlet within 30 to 40 miles of London.

In addition, 2,500 tons of ferrous scrap was taken to the blast furnaces for smelting down into pig iron; 2,000 tons of paper were recovered for board making; and 2,500 tons of kitchen waste were collected in the area, making a total of about 19,000 tons extracted—by simple methods—from the 46,000 tons of refuse collected (about 40 per cent).

Mr Gurney said that Tottenham Cleansing Department were concerned not so much with what they extracted and sold from the refuse but with what to do with the other 60 per cent. It consisted mainly of the "tailings" of refuse after the dust, cinders, metal, etc., had been extracted. Those tailings were at present passed through incinerators, the heat generated being used for the processing of waste food. The Tottenham waste-food-processing plant dealt with about one-sixth of the total production of concentrated kitchen waste in the country, the collections being dealt with from about eighteen neighbouring authorities. About 50 per cent of the heat needed for the processing was obtained from the burning of the unsaleable refuse.

A plant was being installed with the object of producing a material

which could be composted. It was not proposed to install an elaborate system for composting the material at the works but it was desired to produce a raw material from refuse which could be utilized for compost. They had not yet been approached by the farmers with an offer to take that material for agricultural purposes. As in so many other cases with the utilization of refuse, the local authority must take the risk of putting in the plant, produce the product and then find a market for it. Did the Author agree that they were on the right lines by taking out the dust and cinder content, a substantial portion of the paper, glass, and rags, and pulverizing the remainder—which was mainly organic refuse—into something which would pass a 2-inch mesh.

Mr C. D. C. Braine referred to some interesting experiments now being carried out near Jerusalem. The refuse was dumped into long heaps about 6 feet wide and 3 feet high and it was then sprinkled with very strong anaerobic sewage obtained from a small plant nearby. It was about the strongest sewage he had met. In a very short time, the temperature in the heap started rising and rags, paper, etc., were completely rotted away, falling to powder at the touch. Temperatures of about 140° F. were obtained in 4 to 5 days. Although the process was started by a sprinkle of anaerobic sewage, the process was itself aerobic and the resultant organic ash harboured neither rats nor flies. Nobody could tell him why an anaerobic process should start the process so rapidly.

Some of the rubbish was tipped on to screens, and larvae of all kinds wriggled downwards through the rubbish as the temperature in the heap began to rise. They endeavoured to reach the cool-air zone at the bottom where air entered the heap from beneath the screens. The larvae fell through the screens on the pans and when enough had collected, the pans were emptied and the larvae sold as a protein chicken food—a useful end product to an otherwise potential nuisance, particularly in the tropics or sub-tropics.

The question of composting with sewage sludge had been discussed at Jerusalem, and although that was quite a feasible process, the disparity between the quantity of sludge obtained daily at the sewage works and the quantity required for composting with refuse raised some difficulties. At best it was unlikely that much more than 50 per cent of the sewage sludge could be disposed of in that way, thus leaving an awkward residue of sludge to be disposed of at the sewage disposal works. In any case, since the refuse destructor would probably not be located near the sewage works—it could be and often was, but it was not necessarily the right place from the transport point of view—the sludge which was used for composting would usually have to be pumped some distance to the compost area. Under such circumstances it seemed to be a better proposition to discharge shredded organic matter obtained from the refuse to the sewers so that it could be transported to the sewage disposal works in the sewers themselves and could be disposed of and digested with the other sludge

in the sewage. This organic refuse would not yield much extra gas in the digestion process, but it was saleable as dried sludge.

In an area like Israel, desperately short of humus, anything like that was saleable.

At Reigate an old sedimentation tank alongside the destructor had been converted for use as a primary sludge-digestion tank and waste steam from the destructor was passed into the sludge, which it heated in a very satisfactory manner, promoting active digestion, in an open tank in all weathers. The situation at Reigate would apparently lend itself to a useful full-scale experiment in the digestion of garbage with sewage sludge. That had been done experimentally in America, but Mr Braine knew of no town in Great Britain where it had been carried out as a proper full-scale experiment. It would surely have to be done before long.

Mr Eric Bell confined his comments to the paragraph in the Paper dealing with protective clothing. Over the years, industry had realized that it was an economic proposition to provide all sorts of beneficial services for their employees, and local authorities had found the same. During the war, the Institute of Public Cleansing had set up a Committee to consider the question of protective clothing and had been staggered by the results of some of the inquiries.

The conclusion had been reached that public cleansing was the one service operated by a local authority which dared not stop for a single day unless they were prepared to get rid of piles of refuse in due course. It was therefore essential for the local authority to look after employees to the best of their ability, and the Committee concluded that the best way to do it was to ensure that every man was adequately protected from the weather and was given clothing which, barring accident and certain diseases, would ensure that he could turn out in any weather conditions and do a full day's work. It was not only essential but economic, because every day that refuse was left uncollected meant the employment of additional men the following day.

Local authorities were therefore bound to acknowledge that the provision of protective clothing was essential to 100-per-cent efficiency in public cleansing services. The Institute of Public Cleansing had published a Report giving specifications of various types of clothing and laying down reasonable scales. Some suggested that the scales were too liberal, but Mr Bell disagreed.

Since then there had been further developments. The British Standards Institution were tackling the question and a British Standard would soon be published with specifications covering all types of clothing. Those, in conjunction with the report of the Institute of Public Cleansing, would give complete guidance to every local authority. Mr Bell hoped that by that time the ideal would be achieved of seeing the dustmen and street sweepers adequately protected against any kind of weather.

Mr W. P. Thompson, speaking of controlled tipping, said there had so

far been no comment on the extraction of metal, which could be easily undertaken. It would mean special unloading and re-loading arrangements. Was that the reason nothing had been done about it? Could nothing be done? He agreed that before 1921 and 1922, when nothing had been done, there had not been the same urgency nor the continuous appeal for scrap metal, but what would be done in the future?

Mr A. S. Knolles said that the Author had not drawn sufficient attention to the changes in the type of refuse which had taken place since pre-war days. Would the Author make some comment on the changes which had taken place as a result of separating out the putrescible matter? For instance, the collection of refuse was likely to alter considerably. Mr Knolles's authority (Twickenham) had installed bins for the household collection of kitchen waste, and would install more. They had found that in a week those small bins collected 7·7 lb. of kitchen waste, separate from the household refuse, for each house.

As a result of that proportion of putrescible matter not being placed in the refuse, the refuse was much cleaner, and they had a drier type of refuse to deal with. There were a number of advantages and at the tip there were changes. The temperature did not appear to rise so quickly and the whole material appeared to be much drier. Many local authorities were using heavy plant on their tips. Mr Knolles used a similar British-produced bulldozer to that mentioned by Mr Boast, which was very satisfactory, and there was the following difference at the tip: whereas controlled tipping in the past was not so consolidated nor so dry as at present, they now had tips which appeared to hold moisture—rain—in the upper layers to a greater extent. It was surprising how little of even heavy rain seemed to reach the lower levels. In some cases the water collected on the surface and evaporated fairly easily.

That might affect water pollution and penetration into permeable layers, mentioned by Mr Ilsley. It was true that in chalk subsoils it was possible for water to move as much as 15 miles in a day, but with the new type of tipping, with the top consolidated and a different quality of material, and when the rain did not penetrate the top so easily as in the past, it might be that the water did not often reach the permeable layers.

There were two points which Mr Knolles thought they should remember about vehicles. In selecting vehicles the opinion of the men who were to work them should be sought, for these men were the backbone of the service and could sometimes give useful information; and it was worth while to try to make sure that the men were working happily. The other was that with neat and clean collecting vehicles the public were more ready to co-operate with the local authority and to look after their own bins.

Mr H. E. Orr, speaking about the analysis of refuse, said the mineral ash constituent of refuse should be treated as such and analysed as mineral aggregate in accordance with the appropriate British Standard, using British Standard sieves. The mineral aggregate conformed fairly well to

a soil which could be used for stabilization, and had been used for that purpose.

The Author had mentioned concentrator plants and refuse disposal, and Mr Orr thought they should also consider plants in utilization. The question of concentrates suggested that while it was desirable to sterilize them from the point of view of transmitting disease to the pig, which was an animal designed to live on living tissues of some sort. Could it be that, as a result of feeding large quantities of sterile material to the pig, the ten little pigs tended tô become five little pigs ?

Mr A. Forbes Ilsley said that the disposal of domestic refuse and the consequent risks of pollution were of the greatest importance to a water authority deriving its supplies from deep wells in the chalk.

On p. 111 the Author had stated : " *Land* from which underground water is drawn for domestic use should not be used for controlled tipping." Land from which underground water was drawn was very difficult to define and, in any case, the provisions of Section 21 of the Water Act, 1945, seemed to preclude that suggestion of an unqualified ban on tipping on, say, the chalk, since they only referred, specifically, to the protection of water from any spring well or adit.

Tipping would have to proceed, and in the interests of economy, hauls should be as short as possible ; at the same time the purity of the underground water had to be preserved. Thus in many districts it would be necessary to strike a reasonable balance between the claims of those two essential features of public health engineering.

The water engineer was, quite properly, extremely zealous in the prevention of pollution. He was not well informed concerning the risks arising from refuse and had neither authority nor control over the various operations concerned in its disposal. Whilst the control exercised at the larger tips was generally of the highest order, that was not always the case—it had been found, quite recently, that highly dangerous spent oxide from a near-by gasworks was being used as covering material at a tip which otherwise could fairly be described as well controlled. Many cases of the unauthorized dumping of dangerous trade wastes had also come to light in recent months and, furthermore, the dangers arising from small and comparatively remote tips, which were subject to only limited supervision and control, could not be ignored. Thus the water engineer was bound to view any proposal to deposit refuse on or near the chalk, with the gravest possible suspicion.

The number of tipping sites available was limited and the best use should be made of them. To that end much more information was needed and research might well be instituted concerning the following aspects of the problem :—

The polluting effects of refuse and the period for which such effects persisted after tipping.

The pre-treatment of refuse designed to render it harmless and, at the same time, useful to the community.

The pre-treatment of tipping sites, for example by the deposit of a filtering medium between the refuse and the chalk.

The nature and thicknesses of suitable filtering media.

Finally, it was impossible to over-stress the importance of maintaining the closest co-operation between all those authorities concerned in, or by, the tipping of refuse.

*** **Mr Hal Gutteridge** referred to the Author's list of five methods of disposal, namely, (1) controlled tipping, (2) incineration-separation, (3) direct incineration, (4) pulverization, and (5) composting.

The object of the first three methods was to get rid of the material by dumping or burning with little or no return for the cost; in those methods all the materials valuable to agriculture were lost.

In methods (4) and (5), the object was to benefit the soil; in the case of (4), that was delayed until the decomposition of the material was complete, and then the nitrogen in the materials was not available for plant growth. In the case of (5), the properly matured compost was in a condition slowly to release nitrogen to the soil at a rate at which it could be absorbed.

When composted with sewage sludge or sewage screenings, the materials formed an organic manure which provided the humus essential to the fertility of the soil. It acted as a holder of moisture and a promotor of aeration and drainage, without which conditions soil could not remain healthy.

It was universally realized that it was necessary to return to the soil the equivalent of that which had been taken from it by the harvesting of crops. When that had not been done, the results had been unhealthy soil and lowered vitality giving poor productivity. Silent witnesses of those conditions were to be seen, for example, in the "dust bowls" of the United States and in many other parts of the world.

The pulverization of the refuse was the answer to the fear, expressed by the Author on p. 99, of the danger of fly and vermin encouragement by the exposure of crude refuse. Flies and vermin were attracted by moist materials and the presence of putrefactive gases. Pulverization had the effect of so redistributing the moisture in the resultant homogeneous mass that it was below that which allured them and it did not present the pre-requisite condition of moisture for putrefaction to take place.

Pulverization stations were therefore placed within the town itself, since their operation was not offensive, and the pulverized material was taken to the composting station outside the town, usually at the sewage works.

A lay-out for composting refuse and sewage sludge for a city of 500,000 persons could take the form where there were five pulverizer stations, to which the maximum length of haul of crude refuse would be 3 miles. The

*** This and the following contribution were submitted in writing.—Sec. I.C.E.

salvable materials would be separated where they could be sold within the city and the pulverized material despatched to the works outside the city, where it would be composted with the sewage sludge to form an organic manure.

A typical flow-line for a pulverizer station would be the equipment for the separation of salvable materials and for the pulverizing of the remainder, followed, at the compost station, by the aeration cells—in which the sewage sludge was introduced—the maturative beds, and screening and packing units.

Mr C. A. Sutcliffe referred to the need for special care to be taken with regard to the tipping of refuse on permeable formations overlaying chalk from which water supplies were obtained.

He said that an instance of the direct pollution of a well in the chalk, which was recorded in the Thirty-Fourth Report on The Results of the Bacteriological, Chemical and Biological Examination of the London Waters for the Years 1939–46, occurred at the end of 1943 as the result of tipping refuse into water in a gravel pit, in consequence of which, an important well station supplying nearly 5 million gallons of water a day had had to be taken out of service for 5 months.

At Wilmington Well Station, where that had happened, the chalk was overlain by river gravel ranging in thickness from 11 to 20 feet, and by soil and made ground up to 6 feet in depth. There were two wells to a depth of about 100 feet, lined to 80 feet, with headings at a depth of 98 feet. Two gravel pits, in which was standing water, were situated not far from the site, the nearest extending to within 50 yards of the well workings. The latter pit had been used for 3 months for the disposal of house refuse, road refuse, some burnt-sugar substance, and a large quantity of iron turnings. The water in the pit was found to be acid which had caused solution of the iron; contamination of the underground water took place and a heavy growth of Crenothrix developed in the well.

The remedial measures consisted of treating the gravel pit with slaked lime, and the well workings with chlorine; to protect the well in the future the land in which the gravel pits were situated was purchased. The filling of the pits with approved material such as rubble, hardcore, and fully burnt ashes had been proceeding under strict supervision and no recurrence of the trouble had been experienced.

The occurrence illustrated the rapidity with which a well might become heavily polluted without warning. In the case quoted, the gravel pit which had been the source of the pollution was near the site of the well; it had been shown, however, that water would travel long distances in fissures through chalk in a relatively short time, without being naturally purified. The only safe way, therefore, of ensuring the protection of underground water supplies from pollution (from the disposal of refuse by controlled tipping in areas where there was no impervious cover over the aquifer from which the water was obtained), was to secure the co-operation of the

planning and the local authorities, so that consultation between them and the water undertaking might take place with regard to the sites for tipping refuse and the precautions which should be taken.

The Author, in reply, said that the discussion had raised many interesting points. Mr Boast had made an important one when saying that controlled tipping could be done only when suitable land was available within an economic radius of the area of collection. Most of the domestic refuse collected within the Metropolitan area was being used to reclaim large areas of land along the River Thames beyond Tilbury, and it might well be that other authorities would have to go outside their own boundaries to find suitable land. There were thousands of non-productive acres in Britain, many of which might be rendered fertile by well planned controlled tipping.

Mr Boast and Mr Knolles had referred to the reclamation of disused wet gravel pits by filling with screened refuse dust. If a method of doing that without objection or nuisance could be found, a considerable acreage of valuable land could be reclaimed. Mr Knolles had done some very useful experimental work in that connexion, but the comparatively small percentage of putrescible matter in the dust fouled the water. The next step in that important research would seem to be to find out whether the dust could be rendered safe and suitable for that class of filling work before it left the refuse-disposal works; it was estimated that 350,000 tons were produced annually at the separation-incineration plants in Britain. In view of the urgent necessity to increase food production it would seem that the troublesome problem of rendering that dust "safe" should now be referred to the Department of Scientific and Industrial Research. If and when it was solved attention might be directed to the possibility of pre-treating domestic refuse with the same end in view.

Mr Knolles had enquired as to the effect of separate collections of kitchen waste on the disposal of the remainder by controlled tipping. The two main effects were (*a*) that the physical condition of the refuse to be tipped was improved from the handling point of view, with the result that it packed better and the rate of settlement was reduced, and (*b*) that the maximum internal temperature of the controlled tip during the first 10 to 12 days was reduced from about 140° F. to about 120° F. or less.

The Author suggested that Mr MacDowell's valuable résumé of the kitchen-waste-concentrate scheme might usefully be studied as a supplement to the information given in the Paper.

Mr Dossor had referred to an interesting post-war method of feeding pulverized kitchen waste into pressure concentrators by compressed air. The Author agreed with him that the improvement had resulted in a higher standard of cleanliness within the factory. All handling and treatment operations, when converting any putrescible waste material into feeding stuffs should be carried out under strictly sanitary conditions.

Mr Gurney had asked whether the "tailings" from more or less complete

mechanical separation would be likely to have a value for composting with other materials after being passed through a 2-inch-mesh rotary screen. Much would depend upon the moisture content of the original refuse and the percentage of fermentable material present in the screened mixture. A somewhat similar end product was produced at the large Dutch works at Drente, which, after pulverization, was readily disposed of to expert agriculturists who, as stated in the Paper, claimed that a heavy moisture content helped to prevent soil erosion, whilst the organic content helped to build humus. At the plant referred to, the demand for the soil-improver was based on actual experience of its value, and exceeded the supply.

Mr Braine had referred to the disposal of organic refuse via the sewers and to its subsequent digestion with sewage sludge. The Author had not heard of any scheme of that nature being tried in Britain but some experience had been gained in a number of districts in the United States of America where the *existing* sewers and sewage-disposal works had been found to be adequate for the purpose. Presumably the householders in those districts had agreed to install expensive "garbage grinders" under their kitchen sinks and to meet the cost of a special collection of cans and other articles too large, or unsuitable, for grinding. In Britain it was the custom for local authorities to provide regular collection and disposal services from rate funds, but in many districts in the United States—even in some large ones—the householder entered into a monthly contract with an approved contractor and paid him direct. The success of any disposal scheme which depended upon the production of a useful material must, in the first instance, be related to the type or class of refuse available, and local analyses varied with the climate.

Mr Thompson had raised the question of the recovery of metal at controlled tips. The total metal content of average refuse was less than 5 per cent, so that recovery by special separation and handling equipment, even at tips receiving large tonnages of refuse, had not hitherto proved to be an economic proposition, but it was now reported that the interested industry was to undertake a large-scale experiment at one of the largest controlled tips in Essex, where very considerable quantities of London refuse were disposed of; the result of that experiment would be awaited with keen interest. Incidentally, it would be observed from Table 4 that local authorities had salved and sold for utilization 1,585,921 tons of ferrous metal between October 1939 and July 1947. All modern separation-incineration plants were fully equipped for the recovery of metals from dry refuse.

Mr Orr had inquired whether there was a risk of reducing "ten little pigs to five little pigs" as a result of feeding them with large quantities of sterile material. Mr MacDowall had supplied the answer when saying that about 2½ million tons of concentrate had been produced and sold since 1940 and after 10 years' experience of its feeding values the demand was probably three or four times the present rate of production.

Mr Ilsley had referred to the possible pollution of underground water-supplies as a result of controlled tipping. That method of disposing of "dry" refuse had been used on an ever-increasing scale since the end of the first World War and tens of millions of tons of dry refuse had been so disposed of. During that period the official view had been that when there was a reasonable doubt as to the suitability of a site for a controlled tip—from the standpoint of possible water pollution—it should not be used.

Mr Gutteridge appeared to be under a misapprehension with regard to controlled tipping and separation-incineration. The first of those methods of disposal could be used to improve useless and derelict land and render it fertile; the separated dust which resulted from the second method could be used to improve certain soils.

It was unusual in Britain, and in other countries producing comparable refuse, to base its value as a soil-improver upon its available nitrogen content, which was quite small—about 0·5 per cent or less. The average nitrogen content of ordinary sewage sludge was about the same. (Incidentally, pulverized refuse was not "crude" refuse in the technical sense; the latter term was used to describe untreated refuse.) About 25 years ago it had been observed that a fairly large accumulation of pulverized refuse, stored above ground level near a pulverizing plant (at that time in use in a London borough), had remained free from fly infestation, but the conclusions reached as to the reasons why houseflies avoided the crushed refuse were not those given by Mr Gutteridge. Reports had been received from other countries to the effect that pulverized refuse had remained free from fly infestation, but in those countries, as in Britain, normal domestic refuse had a heavy mineral dust content.

The Author agreed that one effect of pulverization was to distribute moisture—and mineral dust—throughout the mass and that, so far as moisture was concerned, such distribution was valuable when the refuse was to be used on land subject to soil erosion.

Mr Sumner's observations had been drawn from a wide practical experience of all aspects of refuse collection work, including mechanical compression and packing within the collection vehicles, and confirmed the views expressed in the Paper.

The closing date for correspondence on the foregoing Paper has now passed and no contributions, other than those already received at the Institution, can now be accepted.—Sec. I.C.E.

Paper No. 5872

"A New Laboratory for the Study of the Flow of Fluids in Porous Beds"

by

Ernest Carr Childs, Sc.D.

SYNOPSIS

Insight into problems relating to the flow of fluids in porous materials may be gained by rigid mathematical analysis and by various methods of successive approximation, but when the limits of such approaches are reached, further progress can be made only by model or full-scale study of porous materials themselves. The Paper describes an installation for such study, comprising a large sand-tank with provision for controlled artificial rainfall and for drainage. The equipment includes a reservoir divided into sections to form standards of measurement of rate of flow by rise of surface; circulating pumps with a constant-head water-tower; and means for the distant indication and recording of hydraulic potential in the sand body. Provision is made for the subdivision of the sand tank and also of the area sprayed, so that a constant depth of sand may be made to represent greater depths by working to smaller scale.

The propriety of using structureless sand to represent what may well be structured soil is explained; the sand and the soil are regarded as permeable media with measurable permeabilities without distinction between causes of such permeability. The solution of problems in the sand tank can be equated to those in natural materials with the same boundary conditions, provided that the ratio of permeability to velocity of flow of fluid at corresponding points is the same in both cases. The use of sand of high permeability has the advantages both of uniformity and rapid settling, and that it requires high rates of artificial rainfall, which are more readily controlled than low rates.

The system of potential recording is described.

Introduction

Problems involving the flow of fluids in porous beds of considerable extent lie mainly in the fields of land drainage, water supply, and oil-field engineering. For a discussion of the general principles underlying such problems reference should be made to the standard texts [1]; it will suffice to state here that if the boundary conditions of the particular problem are simple, it is often possible to derive a solution by an application of potential theory, making use of any or all of the well-known techniques of conjugate functions, images, hodographs, and so on. A large field of inquiry remains in which such simplifying circumstances are lacking. For example, in the whole of the study of land drainage, and in much of that of water supply, the upper boundary of the effectively conducting medium is a free surface or "water table," whose location must be deduced as part of the solution.

[1] The references are given on p. 141.

Water may emerge from the soil at other free surfaces or "surfaces of seepage." Furthermore, a problem may involve the flow of water above the water table, where the moisture content, and therefore the permeability itself, depend upon the magnitude of the (negative) hydrostatic pressure, or suction, and therefore upon the potential; the permeability is thus a function of the potential and is one of the dependent variables of the problem. Then, again, steady states of flow occur only fortuitously in most drainage problems, and whilst a solution which is a function of time may, in certain circumstances, be obtained as a succession of momentarily steady states, this is a most laborious proceeding even when possible at all.

When analysis has reached its limit of usefulness, recourse may be had to methods of successive approximation. Such methods include numerical reiteration (for example, Southwell's method of relaxation of restraints [2, 3]), the graphical construction of flow-nets as described by Forchheimer [4] (whose method has been described by Casagrande [5]), and the construction of electric analogues, already applied with success to some two-dimensional drainage problems.[6] These methods also have their limitations, and recourse is then had to direct experiment with a porous medium. It is neither necessary nor desirable that the medium chosen should be a naturally occurring body. The property of the body which enters into flow problems is the hydraulic permeability, defined by the constant K in the equation expressing Darcy's law of flow in porous materials:

$$v = -K \, grad \, \phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

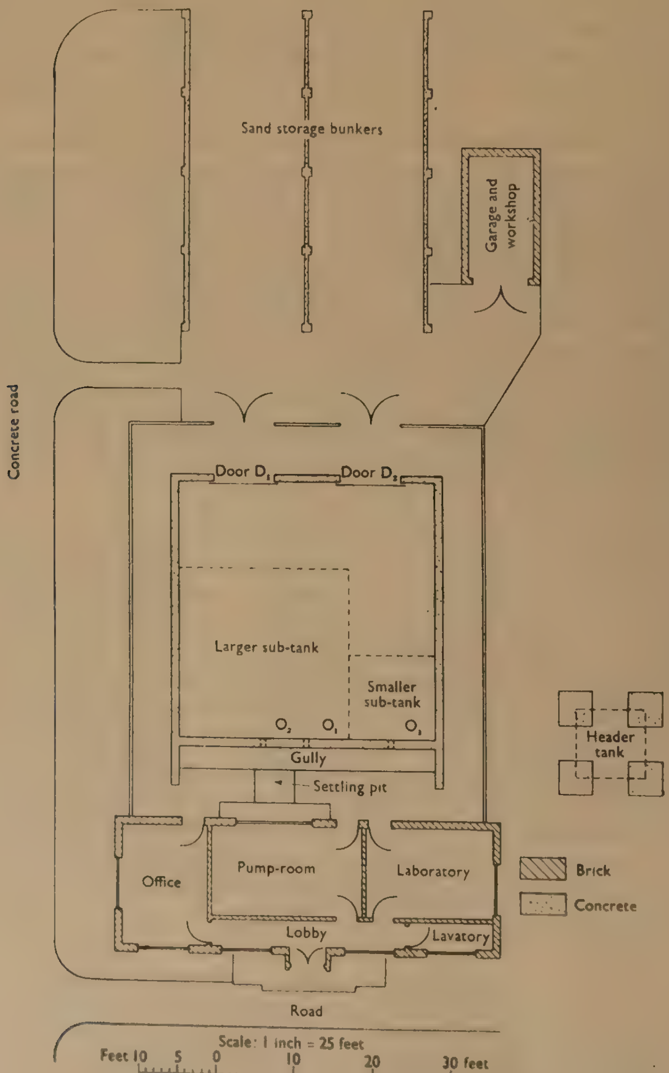
In this equation, v denotes the apparent velocity of flow of the fluid and $grad \, \phi$ denotes the gradient of the potential function, ϕ. If a solution of a problem can be found for given boundary conditions but different permeability, it can be transferred to similar problems with any known permeability; the condition of transference is that the ratio v/K is the same in the cases compared.[7] It is therefore only necessary that there should be available methods for measuring the permeability of natural bodies in the field, together with facilities for reproducing the boundary conditions and solving the hydraulic problem in one selected porous body. It is desirable that this selected body should be an artificial bed with artificially controlled flow of fluid, in order to avoid the complications and frustrations associated the variability of natural bed materials and uncontrollable natural water movements.

Location and Description of Laboratory

For the study of the hydraulic principles of such problems a laboratory was designed shortly after the war, and has now been constructed for the Agricultural Research Council by the Ministry of Works. It is situated on a part of the land occupied by the Cambridge University Farm, and has

in other respects associations with the University School of Agriculture, where developments in this field of soil physics have been centred during the past 15 years. The elements of the installation comprise a large tank of reinforced concrete, filled with a grade of Leighton Buzzard sand of low

Fig. 1

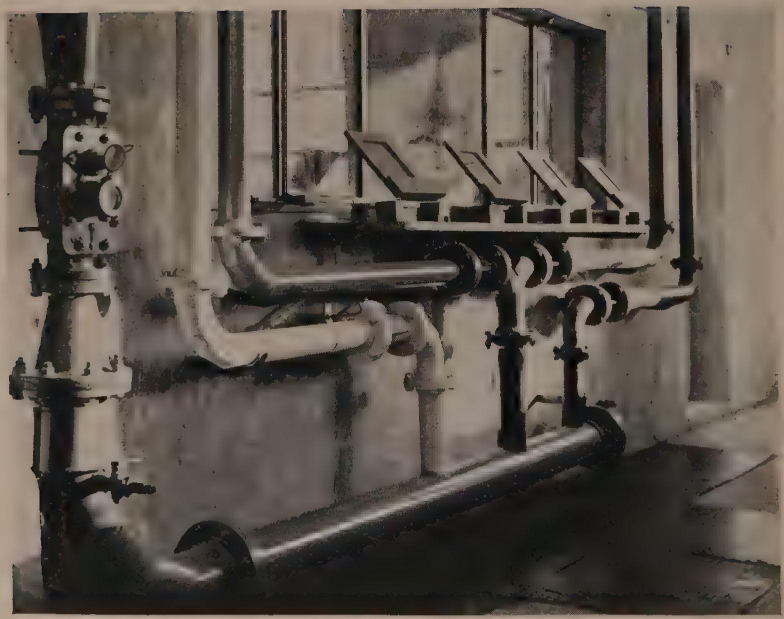


Skeleton Plan of the Installation

Fig. 3

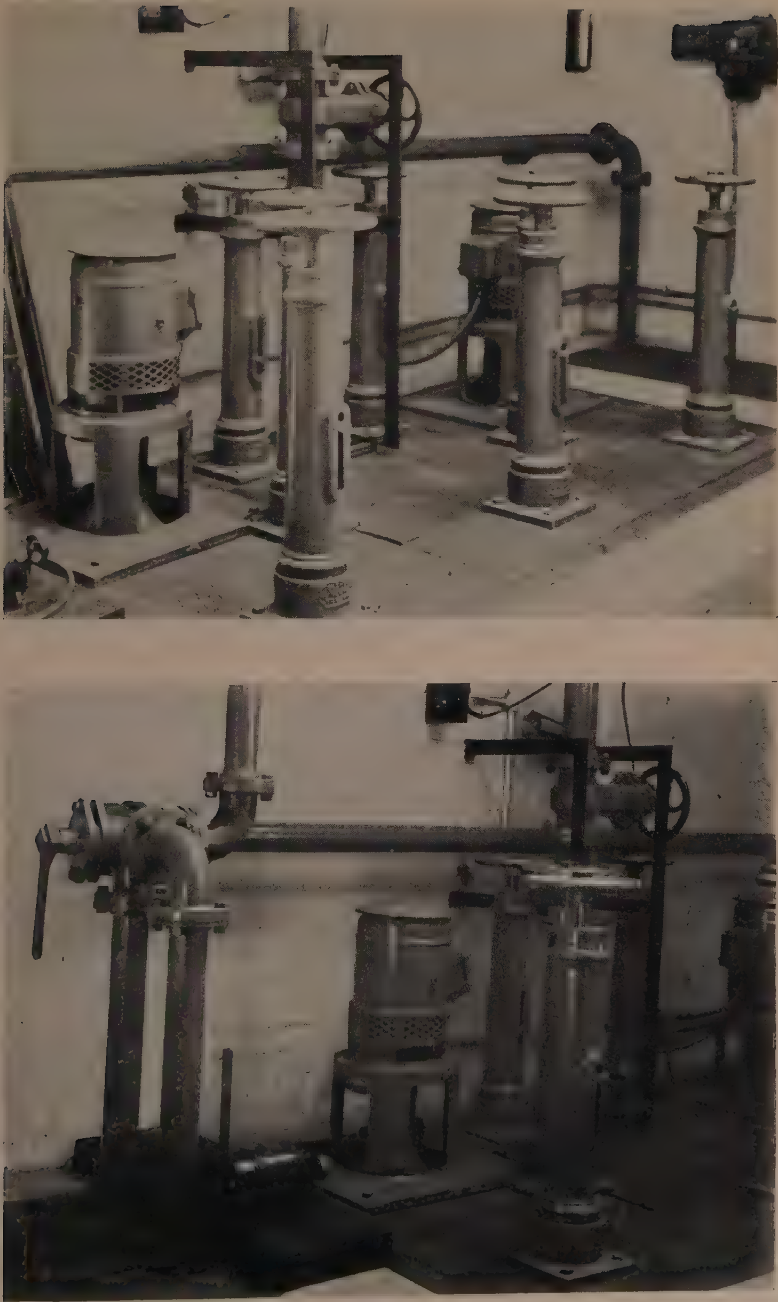
Ported Valves controlling the Area sprayed by each Grid

Fig. 4



Division of the Main Water-Supply Line to feed the four Spray Grids, showing the Separate Control Valves and Pressure Gauges, Actuated or Read from inside the Pump Room

Figs 5



INTERIOR OF PUMP ROOM, SHOWING MOTORS, VALVE HANDWHEELS AND PILLARS, AND OVERFLOW DIRECTING VALVE

Fig. 6

View of a Portion of the Interior of the Tank Room, showing part of the Tank, Spray System, and Travelling Bridge

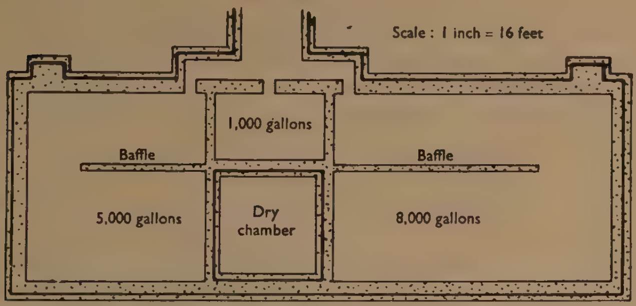
Fig. 7

General View of Exterior of the Installation

soluble content, an overhead spray system for simulating rainfall, provision for drainage and the continuous circulation of water from a reservoir, and means for the remote indication and recording of hydraulic potential in the sand body. *Fig. 1* shows a plan at ground level and *Fig. 2* a plan of the underground reservoir.

The sand tank is 33 feet by 33 feet in plan, with a floor laid with a fall to facilitate drainage to the outfall end, the average depth being 5 feet. Doors D_1 and D_2, made of steel plate, are bolted to seatings embedded in the concrete wall when closed, the joint being sealed with a rubber gasket. Each of these doors is wide enough to admit a standard sand-tipping lorry of 6-cubic-yard capacity, and is aligned with a door in the end wall of the building which houses the tank. This latter building has a light steel frame and corrugated panelling. Two overhead gantries, carrying tipping

Fig. 2



SKELETON PLAN OF RESERVOIR AND DRY PIT, LOCATED BENEATH THE OFFICE AND LABORATORY BLOCK

buckets of 10 cwt capacity, run from the innermost end of the sand tank, through the aligned doors (one through each of the pair) to the farther end of two sand storage bunkers outside the tank building.

As shown by the broken lines in *Fig. 1*, the tank may be subdivided into the smaller tanks by means of sheet-steel panels similar in construction to the doors D_1 and D_2, the sections being bolted to each other and to seatings in the concrete floor, all joints being rubber-sealed. The larger of the two sub-tanks measures 22 feet by 22 feet and the smaller 11 feet by 11 feet, the depth, of course, being the same as for the full-sized tank. The reason for this subdivision is that a maximum depth of 5 feet is not generous provision for the representation of depths of natural beds, but by employing a scale model, scaling down all boundaries, and maintaining the same absolute depth, depths greater than the 5 feet available may be represented. For example, a drain of 6 inches diameter laid at a depth of 2 feet down the middle of the full-sized tank may be regarded, by symmetry, as one of a system of drain lines with an equidistant spacing of

33 feet, in a permeable material of depth which cannot exceed 5 feet. If the smaller (11-foot-square) sub-tank is used, and a drain line of pipes of 2 inches diameter is laid down the middle of this tank, which is filled with sand to a depth of 5 feet, then the results may be interpreted to scale as representing a drain line of 6 inches diameter separated by 33 feet from its neighbours and laid in a bed of 15 feet total depth. The centre-lines of the tanks being the most frequently used sites for drain lines, provision is made for outfalls through orifices in the tank end-wall at various heights on these centre-lines, as shown at O_1, O_2, and O_3 in *Fig. 1*; these outfalls are for the main tank, the larger sub-tank, and the smaller sub-tank respectively.

A steel rail runs along the top of each side wall of the main tank, the two rails forming the track of a manually-operated steel travelling bridge, which permits of access to all parts of the sand surface, both for laboratory workers and for apparatus, without disturbance of the sand. The nature of the experiments carried out in the tank and the type of apparatus used will not be discussed in this Paper, since the first part of a programme of work has now been completed and an account is being prepared for publication elsewhere.

A little more may profitably be said about the material in the tank. It has already been made clear that it is unnecessary and undesirable that this should be a natural material *in situ*; it need hardly be stressed that it cannot be a natural material transported to the tank, for structured materials cannot be so transported without destroying the structure which gives them their characteristics as permeable materials. Sand, on the other hand, quickly settles down to a final state of packing and provides a uniform medium. Its high permeability relative to that of many natural soils is a further advantage, since, as already indicated, this requires a proportionately higher velocity of flow of fluid to reproduce a given potential distribution and flow-net. Consequently, rates of precipitation of the artificial rainfall must be correspondingly heavy, and it is a fact that it is much easier to control such high rates in respect of uniformity and reproducibility than it is to control lower rates typical of natural rainfall in Britain.

The spray system for producing the controlled precipitation comprises four separate grids of nozzles. The pattern of each grid is that of a square mesh of 50-inch interval, a nozzle being located at each mesh intersection, and the whole being at a height of 100 inches above the surface of the sand in the tank. Each grid separately gives a sufficiently uniform precipitation at the surface, and all four are accommodated by offsetting each slightly from the others. The nozzles are of the swirl type, and each grid has a different spray rate at the working pressure. This pressure is supplied by a constant-head water-tower of 1,000 gallons capacity at a height of about 35 feet above the plane of the nozzles, and at this head the spray rates of the four grids are equivalent to rainfall rates of 10·6, 4·6,

2·5, and 1·9 inches per hour respectively. By suitable combinations of grids in use there is a considerable range of precipitations available—from 1·9 to 19·6 inches per hour in fifteen easy stages. Further control is obtainable, if desired, by a separate rubber-diaphragm-type regulating valve in each grid supply, but such control is dispensed with if possible, since the advantages of constant-head supply are not wholly retained. One further control of different type is incorporated. When only the smaller tanks are in use it may be desirable to spray only that smaller area, so that other work may be carried on in the space left. Four ported valves in the grid supply pipes, shown in *Fig. 3*, arrange for this selective spraying.

The water used in experiments is circulated, the reservoir being the basement of the " office block " shown in *Fig. 1*. As shown in *Fig. 2*, the reservoir is of reinforced concrete, " tanked " with bitumen to render it truly watertight. It is subdivided into three reservoir compartments and a dry pit. The capacities of the compartments when filled to a depth of 4 feet are respectively 8,000, 5,000, and 1,000 gallons. The reason for this subdivision is that the reservoir forms the volumetric tanks which are the primary standard of measurement of rate of flow, the measurement being, of course, the rate of rise of the surface in a still well in each compartment. The different horizontal areas provide for accuracy of measurement of different ranges of rate of flow. Flowmeters of conventional form [8] are used for routine measurements, and are standardized against the volumetric tank measurements.

The dry pit houses the pumps, driven by vertical shafts from motors mounted on steel cover plates in the pump-room above. A pipe through the wall of each reservoir compartment connects, through a screw-down valve, to a common lead, which in turn delivers to two " Pulsometer " centrifugal pumps in parallel, each with its own isolating valves ; thus either or both may be used according to demand. All valves are operated through shafting from the pump-room above. The pumps deliver only to the header tank of the constant-head tower, from which an overflow pipe leads back to the pump-room and thence, via a selector valve, to any of the reservoir compartments. The supply pipe from the header tank to the spray system passes direct into the tank building. The water passes first through an integrating type of water meter, and is then divided into four streams, each of which passes to one of the nozzle grids via one of the rubber-diaphragm valves already mentioned, the valves being operated from the pump-room. This section of the supply system, from the integrating meter to the delivery side of the control valves, is shown in *Fig. 4*. The interior of the pump-room, showing the motors, the valve pillars, and the return overflow pipe and valve is depicted in *Figs 5*. Any drainage water from the tank is first metered and then discharged into a gully, from which it passes a sand-settling pit and is then run into a second gully, from which it is admitted to any of the reservoir compartments

by sliding doors lifted by handles in the pump-room. Thus a continuous precipitation and drainage, up to a rate of 20 inches per hour, may be maintained by the circulation of no more than 14,000 gallons of water. The relation between the size of the reservoir and that of the sand tank is such that the sand may be saturated to the surface while still leaving just enough water in the reservoir to cover the lead pipes to the pumps, and the whole of the drainable water in the sand can be accommodated in the reservoir without its capacity being taxed to the limit.

The effective space in the office block above the reservoir is divided into three rooms—an office, a pump-room and store, and a laboratory (in the restricted sense). The pump-room has been adequately described in the preceding paragraph. It need only be added that it houses (besides the pump-motors, their control panels, and the valve pillars and hand-wheels) rectifying panels to supply low-voltage direct current for experimental purposes. This is a 24-volt supply buffered by a battery of lead-accumulator cells. Observation of the tank, when spray renders the tank building uninhabitable, is possible through a window in this room.

The laboratory room has general functions of the type familiar to all research workers, and in addition has specific uses relating to the operation of the tank. It often arises that measurements of potential in the sand tank cannot be made on the spot, since conditions may preclude the presence of workers in that part of the building. The potential is therefore indicated in the laboratory room. A measurement of potential distribution may involve the measurement of potential at as many as fifty or a hundred points in the sand body, and if the experiment in progress is one involving a non-steady state of flow, this measurement must be completed quickly so that all potentials refer to the same instant of time, or to an interval short in relation to the time taken for appreciable changes of state of flow in the sand. This calls for a means of rapidly recording a large number of potentials, and the apparatus for this is designed to be installed in the laboratory room.

The means adopted for recording potential, though not yet completely installed, is based on a small cell consisting of a "hydroflex" metal bellows, sealed at one end and fitted at the other with an insulating plug through which passes a brass rod; this rod makes contact, through platinum-iridium contact units, with the closed end of the cell. The plugged end is attached to a compressed-air line so that the air pressure in the cell may be controlled at will. The complete cell is enclosed in a brass chamber into which water, but not sand, is admissible through a filter, and the whole is buried at the chosen point in the sand. The bellows is subject externally to hydrostatic pressure equal to that obtaining in the sand at that point, and internally to air pressure which may be altered at will. If the air pressure is steadily increased, the bellows will begin to expand against the water pressure, and the electrical contact will be broken. The air pressure at which this occurs depends upon the external hydrostatic pressure, which

may therefore be measured if the cell is first directly standardized to read hydrostatic pressures. If all the cells are connected to the same air line and the air pressure is steadily increased with time at a known rate, the various cell contacts will break at various times according to the different prevailing hydrostatic pressures; from a record of these times the corresponding air pressures, and thence hydrostatic pressures, can be deduced, the whole process of recording the fifty or a hundred pressures taking only about a minute. The control of the pressure in the air line and the recording of the circuit breaks are performed in the laboratory room.

The Laboratory is provided with a small combined garage-workshop, equipped with a 3½-inch Myford ML7 lathe with a fairly complete set of accessory tools, including a dividing head, for milling and sawing as well as the more usual turning operations.

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The Author wishes to acknowledge his indebtedness to Professor Sir Frank Engledow, F.R.S., whose support was responsible in the first place for bringing the scheme to fruition; and to the Agricultural Research Council, and in particular to its late Secretary, Sir John Fryer, F.R.S., whose persistent endeavours piloted it through the administrative channels. The translation of sketch plans into working drawings and ultimately into a structure has been the responsibility of the architects and engineers of the Ministry of Works. The staff of the Unit of Soil Physics have all contributed to the development of a laboratory out of the inanimate skeleton handed over by the builders, and mention should be made particularly of Mr T. O'Donnell, who devised the system of recording potential distribution described in the text.

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The Paper is accompanied by six photographs and two sheets of drawings, from which the half-tone page plates and the Figures in the text have been prepared.

Paper No. 5875

"The Generalized Gould's Function"

by

Robert Mathieson, B.Sc., Ph.D.

(Ordered by the Council to be published with written discussion) †

In an article in 1901 on flood regulation, Gould [1] introduced his solution to the problem of the rise and fall of water level in a reservoir with flood inflow discharging over a sharp-edged rectangular weir. This solution was extended by Captain Garret [2] to cover the same problem with the surface area varying linearly with surface level and presented in a somewhat different form. Recently, a Paper by Standing and Johnston [3] has brought to to light some small discrepancies in Gould's tabulated values.

Since it seems clear that Gould's problem is one of a series of related problems, some of which are likely to be met with in hydraulic work generally, in connexion with flow into and out of tanks and reservoirs, it is proposed here to assemble the solutions to some of these problems and to make them available in a readily applicable form.

Gould's problem is that of a reservoir of constant surface-area A, taking a constant flood-inflow Q, while discharging over a weir or spillway at the variable rate $q = CLh^{\frac{3}{2}}$, where L denotes the length of the weir, h the head above the crest, and C a coefficient for the particular weir, usually taken as 3·33 if there are no end contractions. Since :

rate of inflow = rate of storage + rate of discharge,

then $$Q = A\frac{dh}{dt} + CLh^{\frac{3}{2}}$$

or the time taken for the surface level to change from h_1 to h_2 is :

$$T = t_2 - t_1 = \int_{h_1}^{h_2} \frac{Adh}{Q - CLh^{\frac{3}{2}}} \quad . \quad . \quad . \quad . \quad (1)$$

This problem is made more general by taking the first two or three terms of a series to represent the area, that is,

$$A = a_0 + a_1 h + a_2 h^2 + \quad . \quad . \quad . \quad .$$

and by writing for the discharge $q = Kh^n$ where K denotes a constant in

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† Correspondence on this Paper should be received at the Institution by the 15th August, 1953, and will be published in Part I of the Proceedings. Contributions should be limited to about 1,200 words.—Sec.I.C.E.

[1] The references are given on p. 147.

a given case, h denotes the head over a discharging orifice, weir, or pipe outlet, and the index n has nominal values applicable as shown in Table 1.

TABLE 1.—VALUES OF n

Case	Small orifice, pipe, or syphon spillway	Pipe with viscous flow	Rect. weir	Parabolic notch (U)	Vee notch	Parabolic notch (cusp)
n	0·5	1·0	1·5	2·0	2·5	3·5

Formula (1) can now be replaced by:

$$T = t_2 - t_1 = \int_{h_1}^{h_2} \left(\frac{a_o + a_1 h + a_2 h^2 + \cdots}{Q - Kh^n} \right) dh\,; \qquad (2)$$

following Gould, $Q = KH^n$ and $r = \dfrac{h}{H}$, so that:

$$T = \frac{a_o}{KH^{n-1}} \int_{r_1}^{r_2} \frac{dr}{1 - r^n} + \frac{a_1}{KH^{n-2}} \int_{r_1}^{r_2} \frac{rdr}{1 - r^n} + \frac{a_2}{KH^{n-3}} \int_{r_1}^{r_2} \frac{r^2dr}{1 - r^n} + \qquad (3)$$

$$= \frac{a_o}{KH^{n-1}} \Big[\phi(r_2) - \phi(r_1)\Big] + \frac{a_1}{KH^{n-2}} \Big[\phi'(r_2) - \phi'(r_1)\Big]$$

$$+ \frac{a_2}{KH^{n-3}} \Big[\phi''(r_2) - \phi''(r_1)\Big] + \qquad . \quad . \quad . \quad (4)$$

where $\phi(r) = \displaystyle\int \frac{dr}{1 - r^n}$; $\phi'(r) = \displaystyle\int \frac{rdr}{1 - r^n}$; $\phi''(r) = \displaystyle\int \frac{r^2dr}{1 - r^n}$ etc.

A useful range of values of the functions $\phi(r)$, $\phi'(r)$, and $\phi''(r)$, calculated as indicated in the Appendix for the six indices shown in Table I, are given in Tables 2, 3, and 4. Interpolation for intermediate values of n (for example, for a side weir n is usually taken as being about 1·65) is possible directly from the Tables when $r < 1$, but when $r > 1$ care should be taken both with variation in increments of r and with variation in the time datum in certain cases owing to the nature of the function; for interpolation purposes the time taken as zero at $r = 10$ would be suitable, and this is effected by deducting $\phi(10)$ from the values for $r > 1$ in the columns concerned.

In problems involving only $\phi(r)$ the estimation of the time for a particular rise in level, or the converse, is straightforward but if $\phi'(r)$ or $\phi''(r)$ is involved, then the rise in level in a given time has to be obtained by trial-and-error methods, as explained by Kanthack[4], that is, by trying several values of h and plotting the calculated time.

Frequently, in practice, the inflow Q will not be constant, but if its variation with time is known or can be estimated then the approximate

procedure usually adopted is to calculate the change in level for each of a suitable number of increments of time, taking the average inflow during a time increment as constant.

TABLE 2.—VALUES OF $\phi(r)$

	0·5	1·0	1·5	2·0	2·5	3·5
0	0	0	0	0	0	0
0·02	0·0221	0·0202	0·0200	0·0200	0·0200	0·0200
0·04	0·0464	0·0408	0·0401	0·0400	0·0400	0·0400
0·06	0·0720	0·0619	0·0406	0·0601	0·0600	0·0600
0·08	0·0994	0·0834	0·0807	0·0802	0·0800	0·0800
0·10	0·1280	0·1054	0·1013	0·1003	0·1001	0·1000
0·12	0·1579	0·1278	0·1220	0·1206	0·1202	0·1200
0·14	0·1894	0·1508	0·1430	0·1409	0·1403	0·1400
0·16	0·2218	0·1744	0·1643	0·1614	0·1605	0·1601
0·18	0·2560	0·1985	0·1858	0·1820	0·1807	0·1801
0·20	0·2913	0·2231	0·2076	0·2027	0·2010	0·2002
0·22	0·3286	0·2485	0·2297	0·2237	0·2215	0·2202
0·24	0·3668	0·2744	0·2522	0·2448	0·2420	0·2404
0·26	0·4047	0·3011	0·2751	0·2661	0·2626	0·2605
0·28	0·4483	0·3285	0·2982	0·2877	0·2834	0·2807
0·30	0·4918	0·3567	0·3220	0·3095	0·3043	0·3010
0·32	0·5380	0·3857	0·3463	0·3317	0·3256	0·3213
0·34	0·5839	0·4155	0·3708	0·3541	0·3468	0·3418
0·36	0·6329	0·4463	0·3961	0·3789	0·3684	0·3623
0·38	0·6841	0·4780	0·4219	0·4001	0·3902	0·3829
0·40	0·7373	0·5108	0·4482	0·4237	0·4123	0·4037
0·42	0·7936	0·5447	0·4755	0·4477	0·4347	0·4246
0·44	0·8508	0·5798	0·5033	0·4722	0·4575	0·4457
0·46	0·9120	0·6162	0·5320	0·4973	0·4809	0·4670
0·48	0·9674	0·6539	0·5614	0·5230	0·5047	0·4885
0·50	1·0426	0·6931	0·5920	0·5493	0·5282	0·5104
0·52	1·1123	0·7340	0·6232	0·5763	0·5528	0·5324
0·54	1·1857	0·7765	0·6560	0·6042	0·5779	0·5548
0·56	1·2633	0·8210	0·6897	0·6328	0·6037	0·5777
0·58	1·3545	0·8675	0·7248	0·6625	0·6303	0·6009
0·60	1·4309	0·9163	0·7615	0·6932	0·6574	0·6247
0·62	1·5206	0·9676	0·7997	0·7250	0·6856	0·6489
0·64	1·6196	1·0217	0·8396	0·7682	0·7148	0·6739
0·66	1·7215	1·0788	0·8817	0·7928	0·7451	0·6996
0·68	1·8329	1·1394	0·9260	0·8291	0·7767	0·7259
0·70	1·9516	1·2040	0·9729	0·8673	0·8100	0·7537
0·72	2·0785	1·2730	1·0218	0·9077	0·8448	0·7835
0·74	2·2154	1·3471	1·0757	0·9505	0·8815	0·8121
0·76	2·3650	1·4271	1·1299	0·9963	0·9205	0·8435
0·78	2·5287	1·5141	1·1946	1·0454	0·9622	0·8772
0·80	2·7089	1·6094	1·2619	1·0986	1·0087	0·9128
0·82	2·9087	1·7148	1·3352	1·1568	1·0496	0·9512
0·84	3·1336	1·8326	1·4164	1·2212	1·1108	0·9929
0·86	3·3906	1·9661	1·5090	1·2934	1·1698	1·0386
0·88	3·6883	2·1203	1·6162	1·3758	1·2381	1·0895
0·90	4·0430	2·3026	1·7414	1·4722	1·3207	1·1510
0·92	4·4794	2·5257	1·8941	1·5890	1·4151	1·2225
0·94	5·0550	2·8134	2·0890	1·7380	1·5365	1·3122
0·96	5·8457	3·2189	2·3627	1·9460	1·7048	1·4354
0·98	7·2223	3·9120	2·8383	2·2975	1·9883	1·6410
0·99	8·6028	4·6052	3·2925	2·6465	2·2688	1·8420

TABLE 2 (*Continued*).—VALUES OF $\phi(r)$

	0·5	1·0	1·5	2·0	2·5	3·5
1·01	16·4560	6·8024	4·4948	2·6515	1·8639	1·1368
1·02	15·0589	6·1093	4·0426	2·3074	1·5902	0·9395
1·04	13·6729	5·4161	3·5795	1·9661	1·3185	0·7485
1·06	12·8489	5·0106	3·3202	1·7681	1·1621	0·6395
1·08	12·2677	4·7230	3·1297	1·6293	1·0526	0·5644
1·10	11·8105	4·4998	2·9838	1·5223	0·9692	0·5070
1·12	11·4355	4·3175	2·8654	1·4359	0·9010	0·4626
1·14	11·1177	4·1633	2·7658	1·3635	0·8449	0·4242
1·16	10·8417	4·0298	2·6798	1·3014	0·7976	0·3926
1·18	10·5951	3·9120	2·6046	1·2471	0·7559	0·3655
1·20	10·3763	3·8067	2·5374	1·1990	0·7192	0·3418
1·25	9·9057	3·5835	2·3964	1·0986	0·6421	0·2924
1·30	9·5166	3·4012	2·2824	1·0184	0·5831	0·2547
1·35	9·1853	3·2470	2·1872	0·9521	0·5342	0·2248
1·40	9·8954	3·1135	2·1055	0·8959	0·4930	0·2003
1·45	8·6364	2·9957	2·0341	0·8473	0·4581	0·1801
1·50	8·4040	2·8904	1·9708	0·8047	0·4274	0·1631
1·60	7·9944	2·7080	1·8630	0·7332	0·3675	0·1349
1·70	7·6425	2·5539	1·7734	0·6750	0·3369	0·1138
1·80	7·3323	2·4204	1·6968	0·6264	0·3040	0·0975
1·90	7·0541	2·3026	1·6312	0·5851	0·2766	0·0844
2·00	6·8016	2·1972	1·5730	0·5493	0·2533	0·0725
3	5·0265	1·5041	1·2174	0·3466	0·1315	0·0259
4	3·8669	1·0986	1·0337	0·2554	0·0843	0·0125
5	2·9709	0·8109	0·9155	0·2027	0·0599	0·0072
6	2·2250	0·5878	0·8310	0·1682	0·0456	0·0045
7	1·5665	0·4055	0·7665	0·1439	0·0361	0·0031
8	1·0033	0·2513	0·7151	0·1257	0·0285	0·0022
9	0·4804	0·1178	0·6729	0·1116	0·0247	0·0016
10	0	0	0·6376	0·1003	0·0211	0·0013
∞	$-\infty$	$-\infty$	0	0	0	0

Table 3.—values of $\phi'(r)$

	0·5	1·0	1·5	2·0	2·5	3·5
0	0	0	0	0	0	0
0·1	0·0069	0·0054	0·0051	0·0050	0·0050	0·0050
0·2	0·0317	0·0231	0·0211	0·0204	0·0202	0·0200
0·3	0·0819	0·0567	0·0498	0·0472	0·0460	0·0452
0·4	0·1686	0·1108	0·0951	0·0872	0·0839	0·0807
0·5	0·3069	0·1931	0·1588	0·1438	0·1361	0·1293
0·6	0·5210	0·3163	0·2523	0·2235	0·2074	0·1922
0·7	0·8612	0·5040	0·3904	0·3367	0·3067	0·2656
0·8	1·4319	0·8094	0·6080	0·5108	0·4551	0·3962
0·9	2·5738	1·4026	1·0068	0·8304	0·7685	0·6028
0·99	6·9562	3·6152	2·4922	1·9585	1·6821	1·2669
1·01	45·851	15·8978	7·4546	4·2511	3·3605	1·4634
1·1	41·024	13·3998	5·9331	3·0779	2·4312	0·8200
1·2	39·382	12·1012	5·4226	2·7084	2·1446	0·6485
1·4	37·473	11·7135	4·8644	2·3180	1·8532	0·4483
1·6	36·127	11·1080	4·5017	2·0753	1·6804	0·3510
1·8	35·004	10·6204	4·2673	1·8942	1·5566	0·2876
2·0	33·998	10·1972	3·9871	1·7483	1·4605	0·2423
3	29·674	8·5041	3·1017	1·2579	1·1675	0·1271
4	28·615	7·0986	2·4869	0·9436	1·0053	0·0835
5	21·599	5·8109	1·9587	0·7086	0·8971	0·0597
6	17·509	4·5878	1·4975	0·5199	0·8182	0·0454
7	13·301	3·4055	1·0778	0·3620	0·7569	0·0360
8	9·000	2·2513	0·6938	0·2260	0·7078	0·0295
9	4·490	1·1178	0·3361	0·1066	0·6671	0·0247
10	0	0	0	0	0·6328	0·0211
∞	$-\infty$	$-\infty$	$-\infty$	$-\infty$	0	0

TABLE 4.—VALUES OF $\phi''(r)$

	0·5	1·0	1·5	2·0	2·5	3·5
0	0	0	0	0	0	0
0·1	0·0007	0·0004	0·0003	0·0003	0·0003	0·0003
0·2	0·0046	0·0031	0·0028	0·0027	0·0027	0·0027
0·3	0·0171	0·0117	0·0101	0·0095	0·0093	0·0091
0·4	0·0481	0·0308	0·0258	0·0237	0·0226	0·0217
0·5	0·1112	0·0681	0·0552	0·0493	0·0463	0·0435
0·6	0·2295	0·1363	0·1069	0·0932	0·0856	0·0778
0·7	0·4521	0·2590	0·1969	0·1673	0·1504	0·1331
0·8	0·8829	0·4894	0·3611	0·2986	0·2623	0·2244
0·9	1·8614	0·9976	0·7127	0·5722	0·4883	0·3986
0·99	6·0761	3·1251	2·1449	1·6565	1·3646	1·0239
1·01	218·337	65·388	25·426	11·5412	5·9336	2·8953
1·1	216·401	62·795	23·843	10·3220	4·9678	2·2183
1·2	214·422	61·381	23·258	9·8987	4·6631	2·0012
1·4	212·056	60·734	22·540	9·3956	4·1750	1·8341
1·6	210·084	59·828	21·998	9·0329	4·0189	1·6238
1·8	208·137	58·950	21·522	8·7261	3·8093	1·5163
2·0	206·227	58·197	21·075	8·4490	3·6274	1·4307
3	195·397	54·004	18·943	7·2463	2·9126	1·1578
4	181·308	49·099	16·732	6·1551	2·3513	1·0010
5	163·229	43·311	14·362	5·1024	1·8676	0·8948
6	140·561	36·588	11·820	4·0679	1·4346	0·8167
7	113·441	28·906	9·107	3·0436	1·0382	0·7560
8	81·084	20·251	6·229	2·0254	0·6706	0·7072
9	43·355	10·618	3·191	1·0113	0·3258	0·6667
10	0	0	0	0	0	0·6325
∞	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$	0

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3. B. Standing and S. Johnston, "Gould's Function." J. Instn Civ. Engrs, vol. 36, p. 566 (Dec. 1951).
4. F. E. Kanthak, "The Principles of Irrigation Engineering." Longmans, Green, 1924.

The Paper is accompanied by the following Appendix.

APPENDIX

VALUES OF $\phi(r)$, $\phi'(r)$, AND $\phi''(r)$

The general integral involved is $\int \frac{r^p dr}{1 - r^n}$, where for the first method it is assumed that p and n are integers since if the index n is a fraction $\frac{s}{q}$ then by the substitution $r = x^q$ the indices of the new variable will be integers.

(*a*) If n is odd and $p < n$.

Factorizing the denominator:

$$1 - r^n = (1 - r) \prod_{m=1}^{m=\frac{n-1}{2}} \left(r^2 - 2r \cos \frac{2m\pi}{n} + 1\right)$$

and

$$\frac{r^p}{1 - r^n} = \frac{r^p}{(1 - r) \prod_{m=1}^{m=\frac{n-1}{2}} \left(r^2 - 2r \cos \frac{2m\pi}{n} + 1\right)}$$

Now the partial fraction corresponding to any root α is $\frac{\alpha^{p+1-n}}{n(r - \alpha)}$ and therefore:

$$\frac{r^p}{1 - r^n} = -\frac{1}{n}\left\{\frac{1}{r - 1} + 2 \sum_{m=1}^{m=\frac{n-1}{2}} \frac{r \cos \frac{2(p+1)m\pi}{n} - \cos \frac{2m\pi}{n} \cos \frac{2(p+1)m\pi}{n} - \sin \frac{2m\pi}{n} \sin \frac{2(p+1)m\pi}{n}}{\left(r^2 - 2r \cos \frac{2m\pi}{n} + 1\right)}\right\}$$

and

$$\int \frac{r^p dr}{1 - r^n} = -\frac{1}{n}\left\{\log_e(r-1) + \sum_{m=1}^{m=\frac{n-1}{2}} \cos \frac{2m(p+1)\pi}{n} \log_e \left(r^2 - 2r \cos \frac{2m\pi}{n} + 1\right) - 2 \sum_{m=1}^{m=\frac{n-1}{2}} \sin \frac{2m(p+1)\pi}{n} \cdot \tan^{-1} \frac{r - \cos \frac{2m\pi}{n}}{\sin \frac{2m\pi}{n}}\right\} + \text{const.}$$

(*b*) If n is even and $p < n$ it can be shown that:

$$\int \frac{r^p dr}{1 - r^n} = -\frac{1}{n}\left\{\log_e(r-1) + (-1)^{p+1} \cdot \log_e(r+1)\right.$$

$$+\sum_{m=1}^{m=\frac{n}{2}-1} \cos\frac{2m(p+1)\pi}{n}\log_e\left(r^2-2r\cos\frac{2m\pi}{n}+1\right)$$

$$\left.-2\sum_{m=1}^{m=\frac{n}{2}-1}\sin\frac{2m(p+1)\pi}{n}\,.\tan^{-1}\frac{r-\cos\frac{2m\pi}{n}}{\sin\frac{2m\pi}{n}}\right\}+\text{const.}$$

In calculating the value the constants of integration have to be obtained separately for $r<1$ (level rising) and $r>1$ (level falling). The values in Tables 2, 3, and 4 have been calculated with the time zero at $r=0$, level rising, and the time zero at $r=\infty$ (or, where that is inapplicable, $r=10$), level falling. In the case of level falling special care has to be taken in interpolating for intermediate values of n.

A few of the equations for $\phi(r)$ are given with the constants determined as above.

$$n=0{\cdot}5,\ \phi(r)=-2\{\sqrt{r}\log_e(1-\sqrt{r})\}\quad\ldots\quad r<1$$

$$\phi(r)=2\left\{-\sqrt{r}+\sqrt{10}-\log_e\left(\frac{\sqrt{r}-1}{\sqrt{10}-1}\right)\right\}\quad\ldots\quad r>1$$

$$n=1\ ,\ \phi(r)=-\log_e(1-r)\quad\ldots\quad r<1$$

$$\phi(r)=+\log_e\left(\frac{9}{r-1}\right)\quad\ldots\quad r>1$$

$$n=1{\cdot}5,\ \phi(r)=\frac{2}{3}\left\{\log_e\frac{\sqrt{r+\sqrt{r}+1}}{1-\sqrt{r}}-\sqrt{3}\left(\tan^{-1}\frac{2\sqrt{r}+1}{\sqrt{3}}-\frac{\pi}{6}\right)\right\}\quad .\quad r<1$$

$$\phi(r)=\frac{2}{3}\left\{\log_e\frac{\sqrt{r+\sqrt{r}+1}}{\sqrt{r}-1}-\sqrt{3}\left(\tan^{-1}\frac{2\sqrt{r}+1}{\sqrt{3}}-\frac{\pi}{2}\right)\right\}\quad .\quad r>1$$

$$n=2\ ,\ \phi(r)=\tanh^{-1}r=\frac{1}{2}\log_e\frac{1+r}{1-r}\quad\ldots\quad r<1$$

$$\phi(r)=\tanh^{-1}\frac{1}{r}=\frac{1}{2}\log_e\frac{r+1}{r-1}\quad\ldots\quad r>1$$

$n=2{\cdot}5$,

$$\phi(r)=\frac{2}{5}\left\{\log_e\frac{\left(r+\frac{1-\sqrt{5}}{2}\sqrt{r}+1\right)^{\frac{1+\sqrt{5}}{4}}}{(1-\sqrt{r})\left(r+\frac{1+\sqrt{5}}{2}\sqrt{r}+1\right)^{-\left(\frac{1-\sqrt{5}}{4}\right)}}\right.$$

$$\left.+\sqrt{\frac{5-\sqrt{5}}{2}}\tan^{-1}\frac{4\sqrt{r}+1-\sqrt{5}}{\sqrt{10+\sqrt{20}}}-\sqrt{\frac{5+\sqrt{5}}{2}}\tan^{-1}\frac{4\sqrt{r}+1+\sqrt{5}}{\sqrt{10-\sqrt{20}}}\right\}$$

$$+\frac{\pi}{25}\sqrt{25+10\sqrt{5}}\quad\ldots\quad r<1$$

and $$\phi(r)=\frac{2}{5}\left\{\log_e\frac{\left(r+\frac{1-\sqrt{5}}{2}\sqrt{r}+1\right)^{\frac{1+\sqrt{5}}{4}}}{(\sqrt{r}-1)\left(r+\frac{1+\sqrt{5}}{2}\sqrt{r}+1\right)^{-\frac{(1-\sqrt{5})}{4}}}\right.$$

$$+\sqrt{\frac{5-\sqrt{5}}{2}}\tan^{-1}\frac{4\sqrt{r}+1-\sqrt{5}}{\sqrt{10+\sqrt{20}}}-\sqrt{\frac{5+\sqrt{5}}{2}}\tan^{-1}\frac{4\sqrt{r}+1+\sqrt{5}}{\sqrt{10-\sqrt{20}}}\Bigg\}$$

$$+\frac{\pi}{5}\sqrt{5+2\sqrt{5}} \quad . \quad . \quad . \quad . \quad . \quad . \qquad r > 1$$

In many cases the values of the functions can be computed less laboriously by a second method using a series solution; a combination of both methods was used in preparing Tables 2, 3, and 4. With $r < 1$ the series solution is obtained thus :-

$$\int\frac{r^p dr}{1-r^n}=\int\left\{r^p+r^{p+n}+r^{p+2n}+\ldots\right\}dr$$

$$=\text{const.}+\frac{r^{p+1}}{p+1}+\frac{r^{p+n+1}}{p+n+1}+\frac{r^{p+2n+1}}{p+2n+1}+\ldots+\frac{r^{p+(m-1)n+1}}{p+(m-1)n+1}+R_m$$

and taking $t = 0$ at $r = 0$, the constant of integration will be zero, while:

$$R_m=\frac{r^{p+mn+1}}{p+mn+1}\left\{1+\frac{p+mn+1}{p+(m+1)n+1}r^n+\ldots\right\}$$

$$\text{and thus}\quad R_m<\frac{r^{p+mn+1}}{p+mn+1}\cdot\frac{1}{1-r^n}$$

Using the above series the integral can be determined to any desired accuracy by taking sufficient terms in the computation, and checking that the remainder R_m is negligible. However, when r approaches unity the number of terms which has to be taken into account increases greatly and it becomes advantageous to derive a more suitable series. Thus, putting $1 - r^n = \theta$, it is seen that:

$$\int\frac{r^p dr}{1-r^n}=\int\left\{-\frac{1}{n\theta}+\frac{p+1-n}{n^2}-\frac{(p+1-n)(p+1-2n)}{1\,.\,2}\frac{\theta}{n^3}+\ldots\right\}d\theta$$

$$=\text{const.}-\frac{1}{n}\log_e\theta+\frac{p+1-n}{1}\cdot\frac{\theta}{n^2}-\frac{(p+1-n)(p+1-2n)}{1\,.\,2}\frac{\theta^2}{2n^3}+\ \ldots$$

and the constant of integration has to be calculated to agree with the values from the previous series.

With $r > 1$, the corresponding series is obtained by putting $r = \frac{1}{\theta^2}$ and $n = \frac{k}{2}$ when:

$$\int\frac{r^p dr}{1-r^n}=2\int\left\{\theta^{k-2p-3}+\theta^{2k-2p-3}+\ldots\right\}d\theta$$

$$\text{or}\int\frac{r^p dr}{1-r^n}=\text{const.}+2\left\{\frac{\theta^{k-2p-2}}{k-2p-2}+\frac{\theta^{2k-2p-2}}{2k-2p-2}+\ldots+R_m\right\}$$

$$=\text{const.}+\left\{\frac{1}{(n-p-1)\,r^{n-p-1}}+\frac{1}{(2n-p-1)\,r^{2n-p-1}}+\ldots+R_m\right\}^*$$

$$\text{where}\quad R_m<\frac{1}{(mn-p-1)\,r^{mn-p-1}}\cdot\frac{r^n}{r^n-1}$$

The constant of integration is obtained by taking $t = 0$ when $r = \infty$ (or 10 in certain cases).

Again when r approaches unity use is made of the series obtained by putting $1 - r^n = -\theta$ (assuming $0 < \theta < 1$); then:

$$\int\frac{r^p dr}{1-r^n}=\text{const.}-\frac{1}{n}\log_e\theta-\frac{p+1-n}{1}\cdot\frac{n^2}{\theta}-\frac{(p+1-n)(p+1-2n)}{1\,.\,2}\frac{\theta^2}{2n^3}-\ \ldots$$

and the constant of integration has to be calculated to agree with values from the preceding series.

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* Any term of this series for which particular values of n and p make the index of r equal to zero should be replaced by $-\log r$.

CORRIGENDA

Proceedings, Part III, December 1952

Discussion on Works Construction Paper No. 21 (Mr Sully's reply)

p. 373, line 9.—*For* " been more than 6 " *read* " ranged from 3·5 to 4·9 "

After line 13.—*Add* " With regard to the observations made by Messrs Hyatt and Morley [4] as to the small effect of surface irregularities and distortion of caissons during sinking, it was interesting to note that at Uskmouth, where the structure had been perfectly true to shape and free from projections and rivet heads a very high value of skin friction had been observed. That confirmed the views expressed by Messrs Hyatt and Morley and was contrary to those previously given in reference 3."

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